CHAPTER 7 Driven Piles

History

Piles are braced, structural columns that are driven, pushed or otherwise forced into the soil. Early primitive man found that pile foundations were very useful in that they allowed construction of a home high above the water or the land and out of reach of marauding animals and warring neighbors.

Piles can be classified as friction piles in either compression or tension (or both), end bearing piles, or a combination of the two. Piles can also be used to generate lateral stability in foundations. Largely by the expensive method of trial and error, early builders discovered that when soil strata immediately beneath a structure were weak and compressible, the foundation should be lowered until more suitable soils were reached. It has also been discovered that, in some cases, there may be a need to develop a hold-down force through the piling. This is accomplished by driving piles that resist uplifting by utilizing tension forces developed between the soil and the pile.

Two types of foundations were developed through the ages to meet the need of supporting structures on deep soil; piles and piers. Piles, by far, are the more commonly used.

The City of Venice was built in the marshy delta of the Poe River because the early Italians wanted to live in safety from the warring Huns of Central Europe. The buildings of Venice are supported on timber piles, driven centuries ago, through the soft mud onto a layer of boulders below. When the bell tower of St. Mark's, built in 900 A.D., fell in 1902, the timber piles in the foundation were found to be in such a good state of preservation that they were used to support the reconstructed tower.

For centuries, timber was normally used for piles. The first concrete piles were introduced in Europe in 1897, and the first concrete piles were driven in America in 1904 by the Raymond Pile Company. Timber piles were usually driven to under 25 Tons bearing, but the new concrete piles were designed for 30 Tons and over. This meant that fewer piles and smaller footings could be utilized for the same imposed loads. Technological advances in the cement and concrete industries made concrete piles cost competitive and, because of this, their use became prevalent.

Pile driving is the operation of forcing a pile into the ground without previous excavation. Historically, the oldest method of driving a pile, and the method most often used today, is by a hammer. No doubt, the earliest bearing piles were driven by hand using a wooden mallet of some sort.

For thousands of years the Chinese and other oriental builders used a stone block as a hammer. It was lifted by ropes and stretched taut by human beings, who were arranged in a star pattern about the pile head. The rhythmic pulling and stretching of the ropes flipped the stone block up and guided the downward blow upon the pile head.

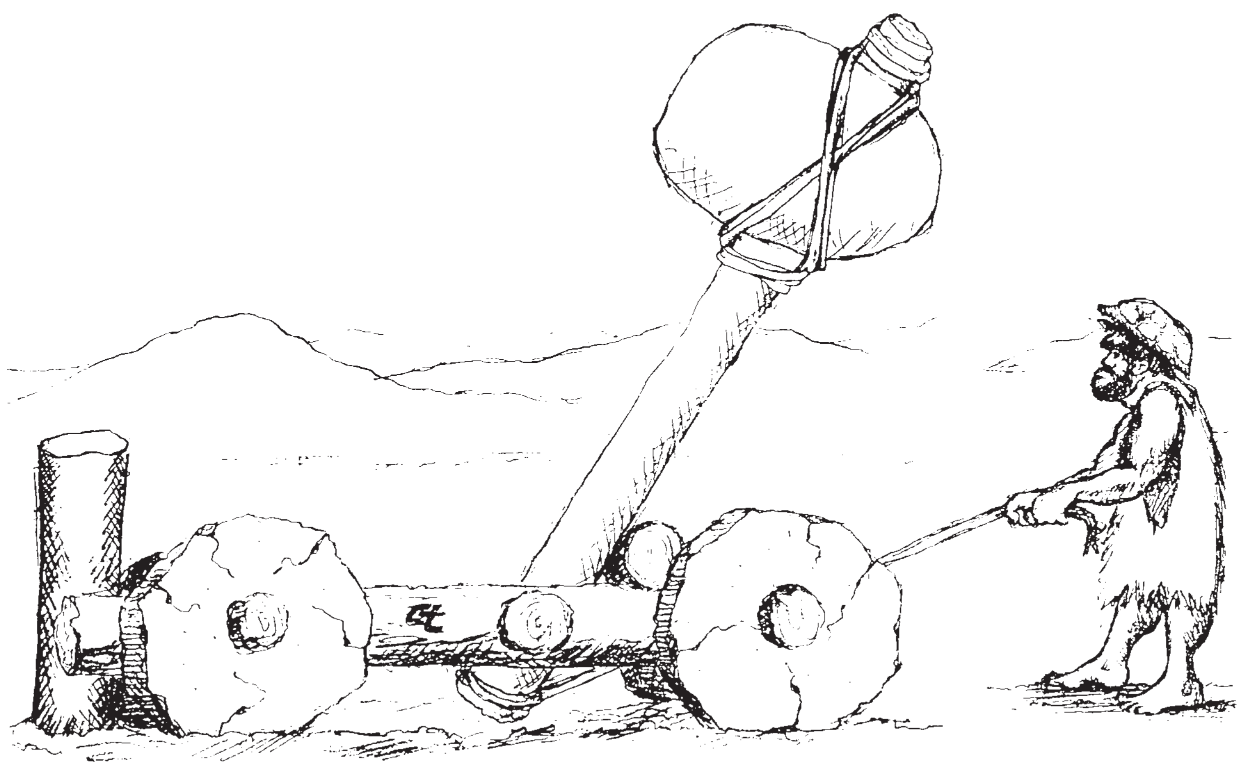


Figure 7-1: Early Pile Hammer

The Romans also used a stone block as a hammer. It was hoisted, first by humans then later by horses, by a rope over a pulley. The downward blow was guided by vertical guides that are similar to pile leads used today. This method continued until the invention of the steam engine which was then used to pull the rope. Further development resulted in steam, air, diesel and hydraulic powered impact hammers plus vibratory and sonic hammers.

Modern day requirements for construction have resulted in various adaptations of the aforementioned pile driving techniques. The remainder of this chapter is intended to outline specifications, equipment, techniques and safety items that a Bridge Engineer can expect to encounter.

General Specifications

Following is a partial list of some of the more important pile driving specifications. Before starting a project, the Engineer should thoroughly review the *Standard Specifications* for general requirements and the Special Provisions for information tailored to the needs of the specific project.

Typical sections of the *Standard Specifications* to be reviewed are as follows:

- Section 19: Earthwork
- Section 49: Piling
- Section 58: Preservative Treatment of Lumber, Timber and Piling

The following are taken from the 1992 *Standard Specifications* and should be reviewed as applicable:

Section 19-6.01: When bridge footings are to be constructed in an embankment, the embankment shall be constructed to the elevations of the grading plane and the finished slope extended to the grading plane before driving piles or excavating for the footing. Rocks, broken concrete or other solid materials larger than 0.33 foot are not allowed in fill where piles are to be driven.

Section 19-6.025: The embankment shall remain in place for the required settlement period before driving foundation piles.

Section 49-1.03: The Contractor is responsible for furnishing piling of sufficient length to develop the specified bearing value, to obtain specified penetration, and to extend into the cap or footing block as indicated on the plans or specified in the Special Provisions. (Estimated tip elevations shown on the plans are used only for estimating the quantity of piling needed for the structure.)

Section 49-1.05: Pile hammers shall be approved steam, air, or diesel hammers that develop sufficient energy to drive piles at a penetration rate of not less than $^{1}/_{8}$-inch per blow at the design bearing value. Steam or air hammers shall be furnished with boiler or air capacity at least equal to that specified by the manufacturer of the hammer to be used. The boiler or compressor shall be equipped with an accurate pressure gauge at all times. The valve mechanism and other parts of steam, air, or diesel hammers shall be maintained in first class condition so that the length of stroke and number of blows per minute for which the hammer is designed will be obtained. Inefficient steam, air, or diesel hammers shall not be used.

Section 49-1.06: Piles, to be driven through embankments constructed by the Contractor, shall be driven in holes drilled or spudded through the embankment when the depth of new embankment is in excess of 5 feet. The hole shall have a diameter of not less than the greatest dimension of the pile cross section plus 6 inches. After driving the pile, the space around the pile shall be filled to ground surface with dry sand or pea gravel. (This is to prevent frictional down drag on the piles due to differential settlement between the new embankment and original ground).

Section 49-1.08: Except for piles to be load tested, driven piles shall be driven to a bearing value of not less than the design loading shown on the plans or specified in the Special Provisions.

Section 49-1.08: When a pile tip elevation is specified, driven piles shall penetrate at least to the specified tip elevations.

Both of the preceding specifications are to indicate that there are in fact two different pile driving requirements: (1) A specific pile tip penetration, and (2) a prescribed bearing value.

Pile Driving Definitions

The following is a partial list of some of the definitions unique to the pile driving trade. These are the most common terms used and should be of benefit to those new to pile driving work. Refer to Figures 7-2 through 7-8 for the location of the defined terms.

TERM	DEFINITION
Anvil	The bottom part of a hammer which receives the impact of the ram and transmits the energy to the pile.
Butt of Pile	The term commonly used in conjunction with the timber piles—the upper or larger end of the pile, the end closest to the hammer.
Cushion Blocks	Usually plywood pads placed on top of precast concrete piles to eliminate spalling.
Cushion Pad	A pad of resilient material or hardwood placed between the helmet and drive cap adapter.
Drive Cap Adapter	A steel unit designed to connect specific type of pile to a specific hammer. It is usually connected to the hammer by steel cables.
Drive Cap Insert	The unit that fits over the top of pile, holding it in line and connecting it to the adapter.
Drive Cap System	The assembled components used to connect and transfer the energy from the hammer to the pile.
Follower	An extension used between the pile and the hammer that transmits blows to the pile when the pile head is either below the reach of the hammer (below the guides/leads) or under water. A follower is usually a section of pipe or "H" pile with connections that match both the pile hammer and the pile. Since the follower may absorb a percentage of the energy of the hammer, the *Standard Specifications* (Section 49.1.05) require the first pile in any location be driven without the use of a follower so as to be able to make comparisons with operations utilizing a follower. In water, the first pile to be driven should be one sufficiently long to negate the need for the follower. The information from the first pile can be used as base information when using the follower on the rest of the piling. Beware of soil strata which may change throughout the length of a footing. Underwater hammers and extensions to the leads can be used as alternatives to driving with a follower.
Hammer Energy	The amount of potential energy available to be transmitted from the hammer to the pile. Usually measured in foot-pounds.
Leads	A wooden or steel frame with one two parallel members for guiding the hammer and piles in the correct alignment. There are three basic types of leads: • *Fixed*, which are fixed to the pile rig at the top and bottom. Refer to Figure 7-4. • *Swinging*, which are supported at the top by a cable attached to the crane. Refer to Figure 7-5. • *Semi-Fixed* or *Telescopic*, which are allowed to translate vertically with relation to the boom tip. Refer to Figure 7-6.
Mandrel	A full length steel core set inside a thin-shell casing for cast-in-place concrete piles. This assists in maintaining pile alignment and preventing the shell from collapsing. It is removed after driving is completed.
Moonbeam	A device attached to the end of a lead brace which will allow a pile to be driven with a side batter.
Penetration	The downward movement of the pile per blow.
Pile Butt	A member of the pile crew other than the operator and oiler.
Pile Gate	A hinged section attached to the pile leads, at the lower end, which acts to keep the pile within the framework of the pile leads.
Pile Hammer	The unit which develops the energy used to drive piles, the two main parts of which are the ram and the anvil.
Pile Rig	The crane used to support the leads and pile driving assembly during the driving operation.
Ram	The moving part of the pile hammer, consisting of a piston and a driving head, or driving head only.
Rated Speed	The number of blows per minute of the hammer when operating at a particular maximum efficiency.
Spudding	Spudding is the driving of a short and stout section of pile-like material into the ground to punch through or break up a hard ground strata to permit pile driving. Used extensively in the driving of timber piles.
Striker Plate	A steel plate place immediately below the anvil. Also known as an anvil.
Stroke	The length of fall of the ram.
Tip of Pile	The first part of the pile to enter the ground.

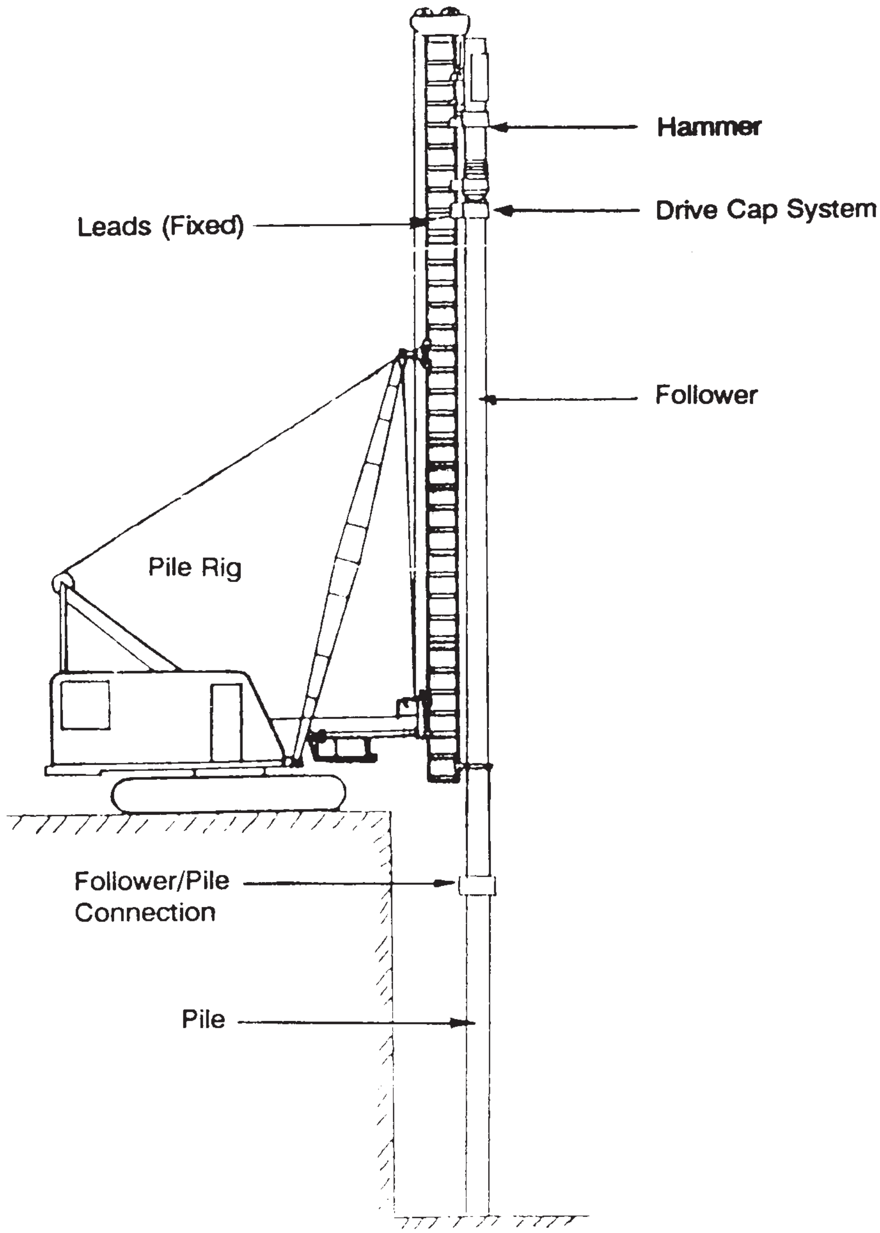


Figure 7-2: Typical Pile Rig Configuration

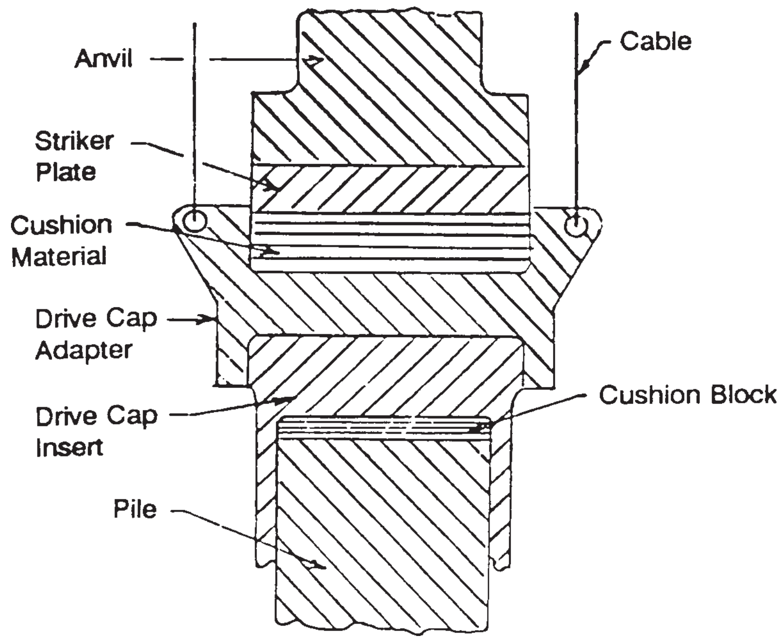


Figure 7-3: Drive Cap System

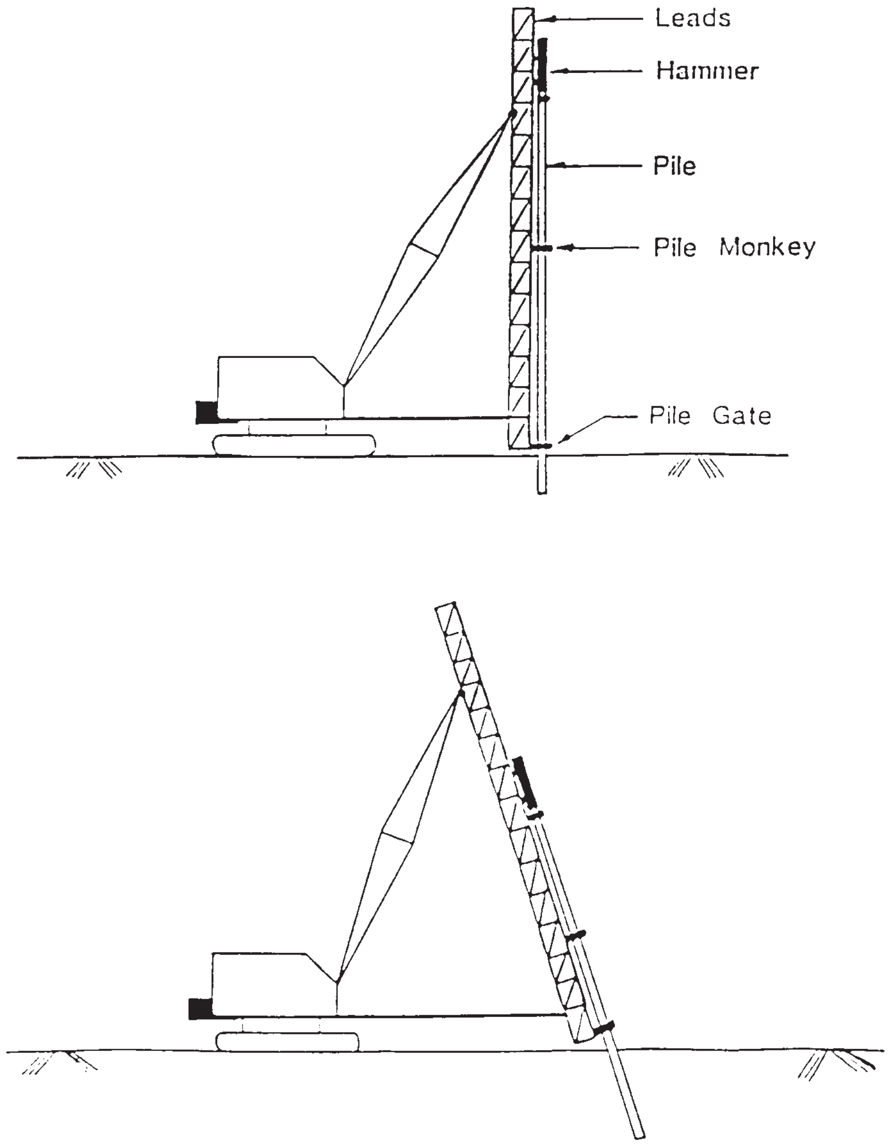


Figure 7-4: Fixed Lead System

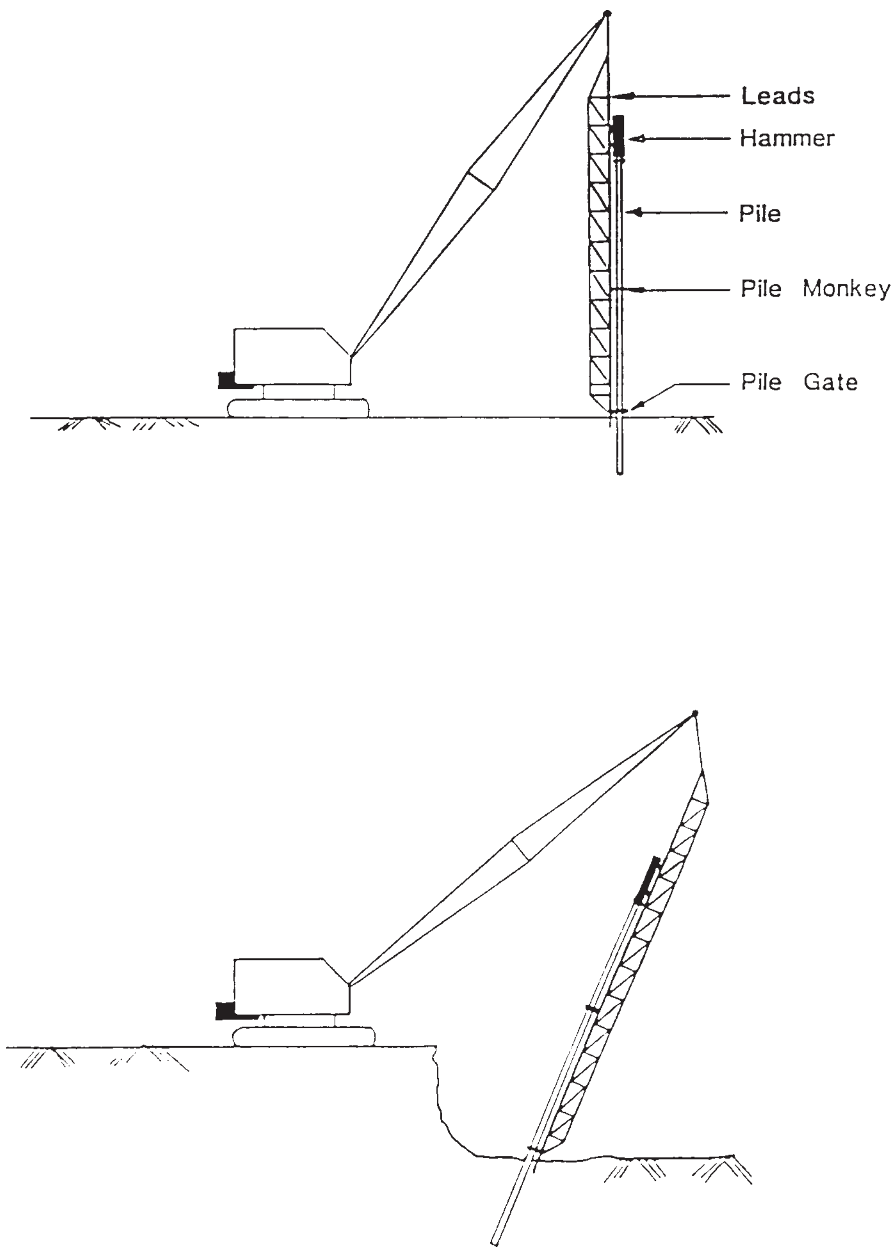


Figure 7-5: Swinging Lead System

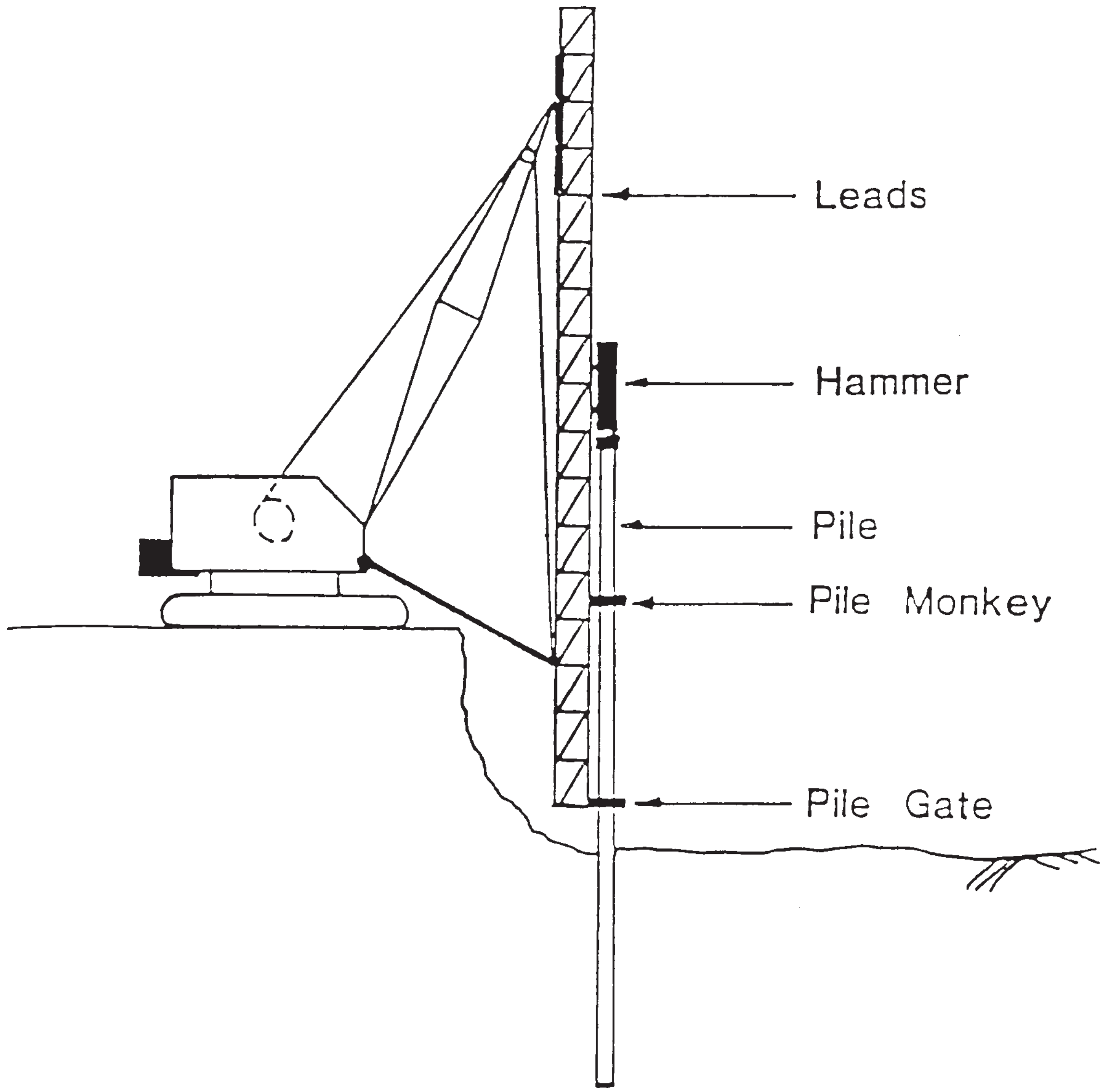
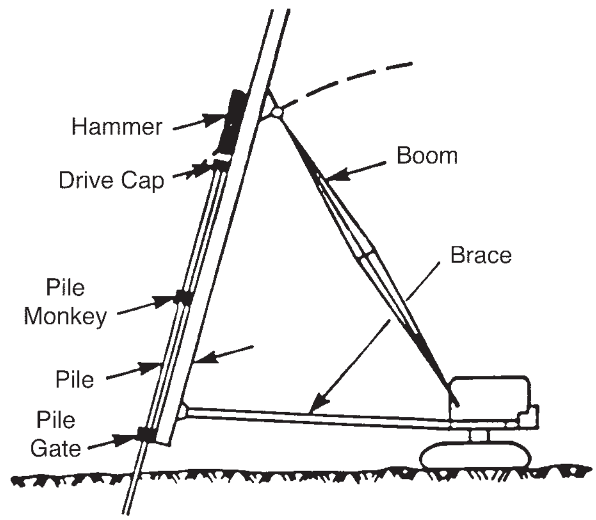
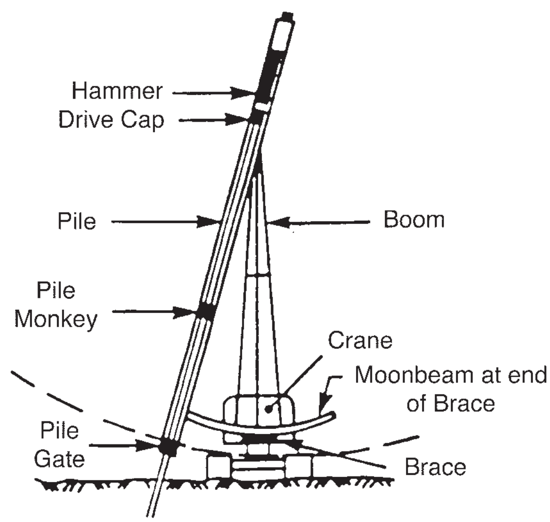


Figure 7-6: Semi-Fixed Lead System



(a) Fore (Positive) Batter



(b) Side Batter by Moonbeam

Figure 7-7: Lead Configurations for Battered Piles

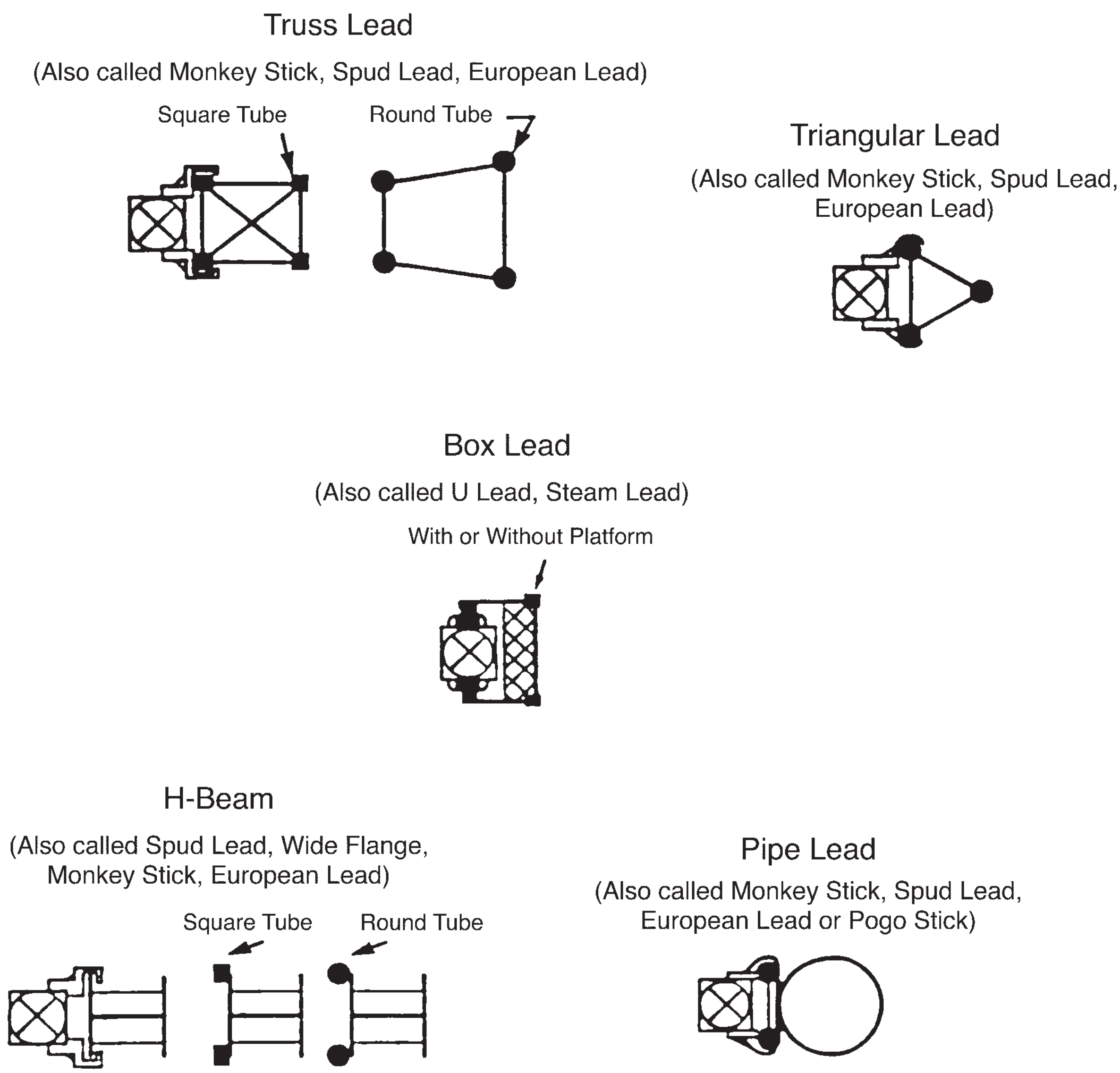


Figure 7-8: Lead Types

Hammer Types

Many different hammer types are used in the pile industry today. In the very recent past one could expect to see, predominantly, the single acting diesel hammer in use on most jobs. With the onset of retrofit work and new construction in areas with low overhead clearances, the use of double/differential acting hammers and hammers that require only a limited overhead clearance are finding their way to the job site. Specific job requirements, be it limited space, noise levels, or unusual tip or bearing requirements will tend to dictate the type of hammer used.

The pile hammer is not only the production tool for the Contractor, it is also a measuring device for the Engineer. A working knowledge of pile hammers, their individual parts and accessories, and their basis for operation and the associated terminology is essential for the Engineer.

Following is a partial list of different types of hammers available today with a brief description of their limiting characteristics.

The Drop Hammer

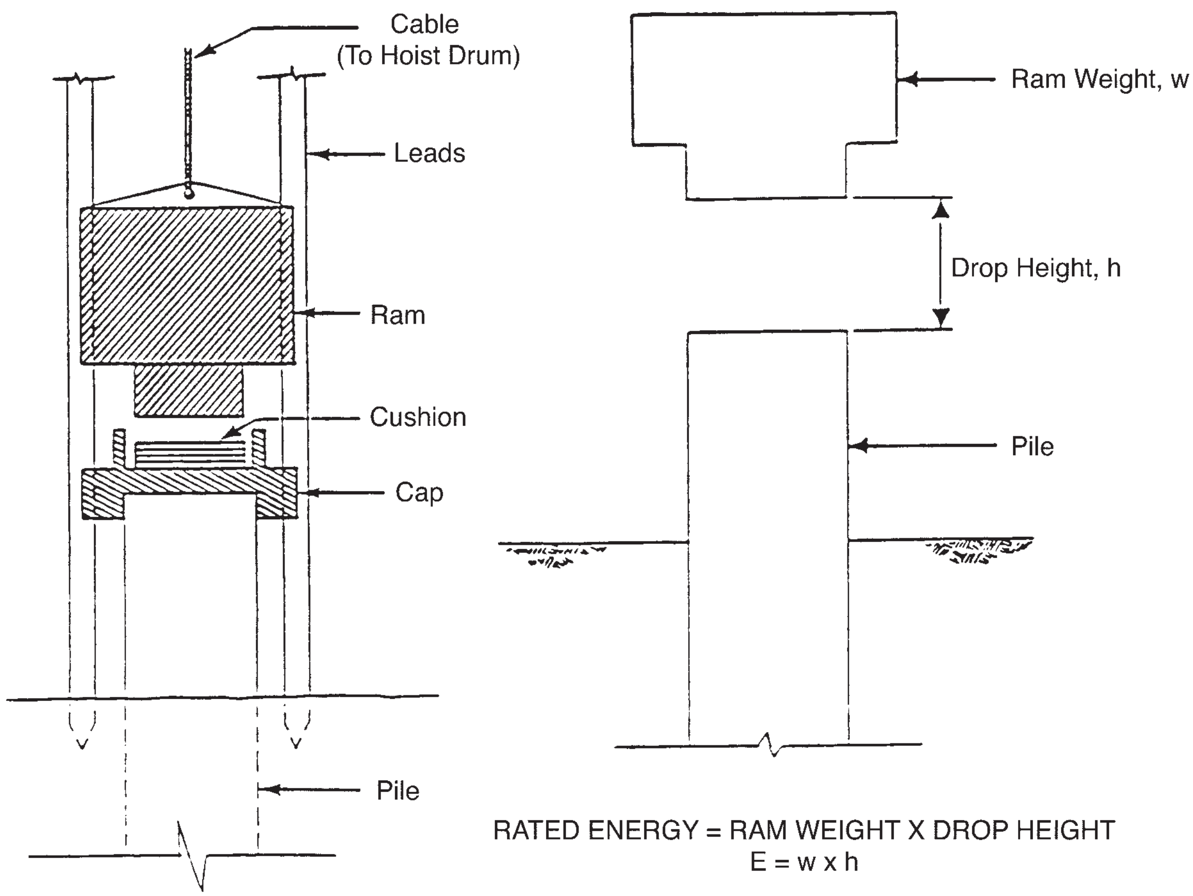
Invented centuries ago, the drop hammer is still in use today. Although modernized somewhat, the basic principle of operation remains the same. A weight is lifted a measured distance by means of a rope or cable and allowed to drop, striking a pile cap block. The available potential energy is calculated by multiplying the known weight of the hammer times its height of fall.

One variation of the drop hammer currently finding its way to the job site is one which requires only a minimal amount of head room. The idea is one which utilizes a pipe pile with a large enough diameter to allow the pile hammer to move up and down inside the pipe's walls. The hammer impacts onto a "stop" built into the bottom, inside of the pipe pile. As the pile is driven, the impact occurs near the tip of the pile. In fact the pile is actually pulled down into position in lieu of being pushed. This configuration minimizes the need for the additional overhead clearance (leads, crane, etc.).

This type of hammer is limited to use only when specifically allowed by the Special Provisions. Hammer weight and stroke restrictions will be found in Section 49-1.05 of the *Standard Specifications*.

The Engineer should:

NO.	ITEM DESCRIPTION
1	Ensure that you have the correct weight for the hammer being used. If in doubt, have it weighed.
2	Ensure the drop hammer lead sections are properly aligned and that all lead connections are properly tightened.
3	Ensure, while in use, that the hoist line is paying out freely.



Basic Components of a Drop Hammer

Rated Energy of a Drop Hammer

Figure 7-9: Drop Hammer

Single Acting Steam/Air Hammer

The single acting steam/air hammer is the simplest powered hammer. Invented in England by James Nasmyth in 1845, it has been used in this country since 1875.

As shown in Figure 7-10, the hammer consists of a heavy ram connected to a piston enclosed in a chamber. Steam or air is supplied to lift the ram to a certain height. The lifting medium is then exhausted and the ram allowed to fall by its own weight.

The rated energy of the single acting steam/air hammer is calculated by multiplying the ram weight (total weight of all moving parts: ram, piston rod, keys, slide bar, etc.) times the length of stroke.

These hammers have a stroke of between 30 and 40 inches and operate at 60 to 70 strokes per minute. They are rugged and deliver a relatively low velocity heavy blow. The only necessary changes in operation from steam to air are a change in the general lubrication and the hose line specification.

The Engineer should:

NO.	ITEM DESCRIPTION
1	Have the manufacturer's current specifications for the type and model of hammer being used.
2	Ensure all required parts of the hammer are intact and in good operating condition.

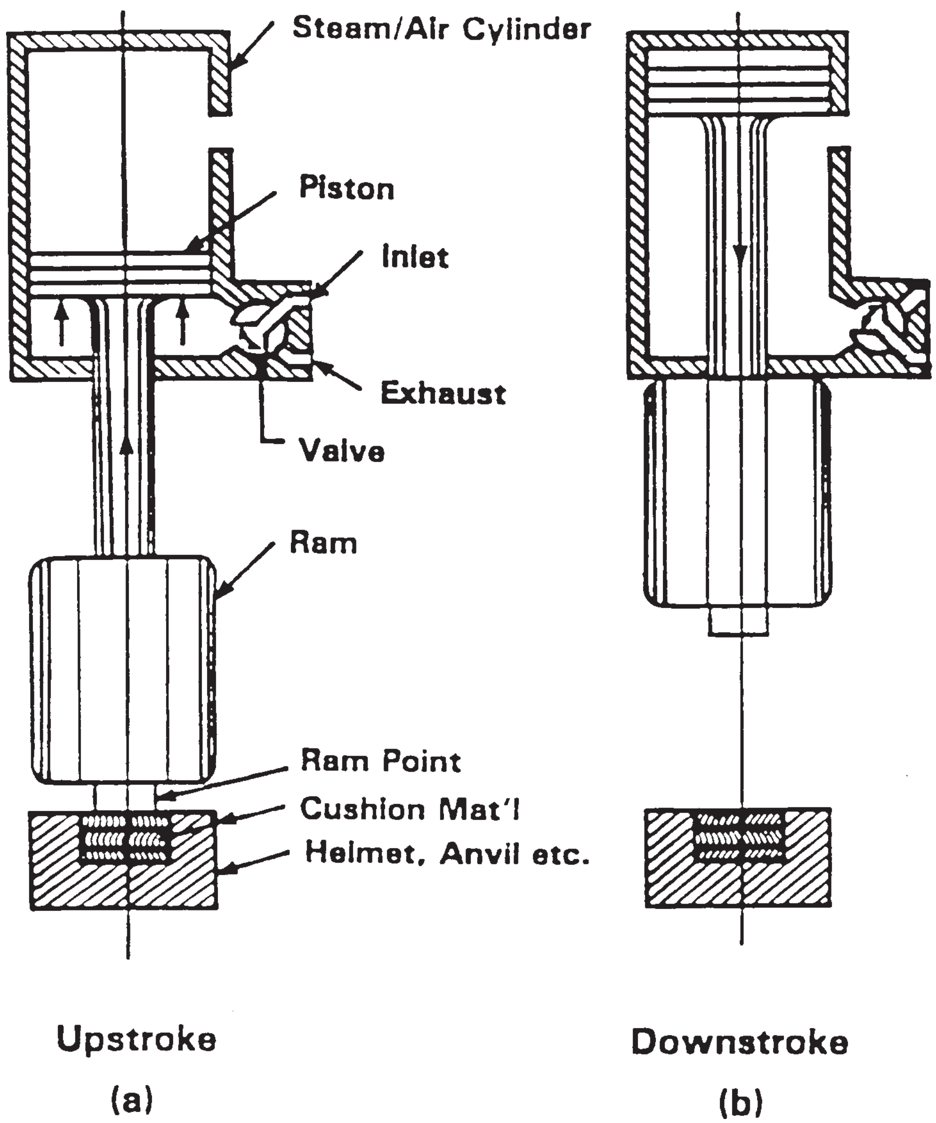


Figure 7-10: Single Acting Steam/Air Hammer

Double Acting Steam/Air Hammers

The single acting steam/air hammer employs steam or compressed air to lift the ram. Once at the top of its stroke, the hammer free falls. With the double acting steam/air hammer, the hammer employs steam or air to not only lift the piston to the top of its stroke, but also to accelerate the piston downward. The energy put into the downward stroke by the compressed air or steam is in addition to the gravitational force utilized by the single acting hammer. Refer to Figure 7-11.

Thus the need for the longer stroke is eliminated with the double acting hammer. It is the reduction of the required stroke that makes these hammers useful when operating with limited overhead clearances. The stroke typically ranges from 10 to 20 inches. The blow rate is more rapid than the single acting hammer, somewhere between 120 and 240 blows per minute.

Some double acting steam/air hammers are entirely enclosed and can be operated submerged in water.

The rated available energy of the double acting steam/air hammer is calculated by multiplying the ram weight times the length of stroke and the effective pressure of the fluid acting down upon the piston head. With this type hammer it is essential that the hammer is operating at the manufacturer's specifications. This requires that the pressure used to drive the hammer be known and that a table be available depicting rated impact energy to the operating speed of the hammer. This type of hammer does not use a cushion block between the ram and the anvil block.

The Engineer should:

NO.	ITEM DESCRIPTION
1	Have the manufacturer's current specifications for the type and model of hammer being used.
2	Ensure all required parts of the hammer are intact and in good operating condition.
3	Have chart available declaring rated energy vs. operating speed of hammer.

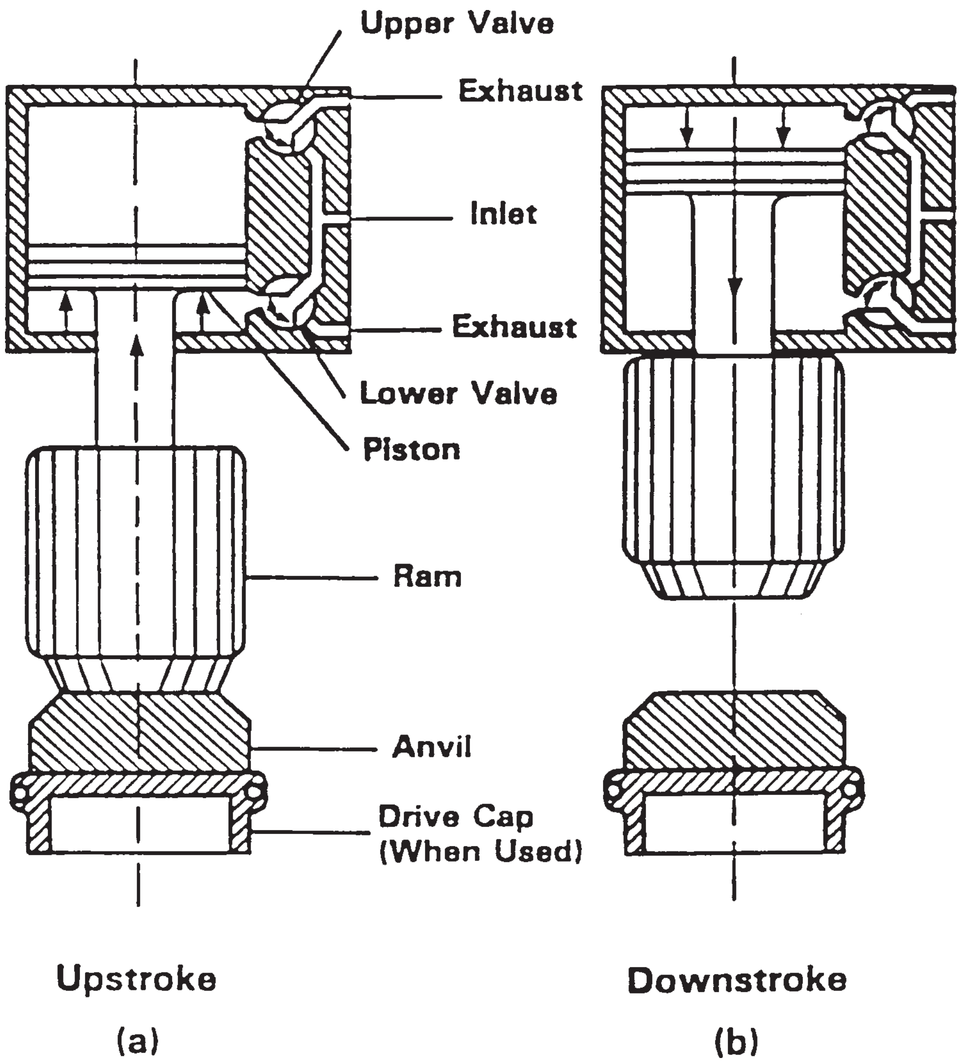


Figure 7-11: Double Acting Steam/Air Hammer

Differential Acting Steam/Air Hammer

The differential acting steam/air hammer is similar to a double acting hammer. Compressed air or steam (motive fluid) is introduced between large and small piston heads to lift the ram to the top of its stroke. Motive fluid is then introduced over the large piston head to accelerate the ram in its down stroke. Refer to Figure 7-12.

The rated striking energy delivered per blow by a differential acting steam/air hammer is calculated by adding the differential force due to the motive fluid pressure acting over the large piston head to the weight of the striking parts and multiplying this sum by the length of the piston stroke in feet. The differential force results from the fluid pressure acting on the top piston head surface minus the same pressure in the annulus acting on the bottom surface and is equal to the area of the small piston head times the fluid pressure. This type of hammer uses a cushion block between the ram and the helmet.

The Engineer should:

NO.	ITEM DESCRIPTION
1	Have the manufacturer's current specifications for the type and model of hammer being used.
2	Ensure all required parts of the hammer are intact and in good operating condition.
3	Have chart available declaring rated energy vs. operating speed of hammer.

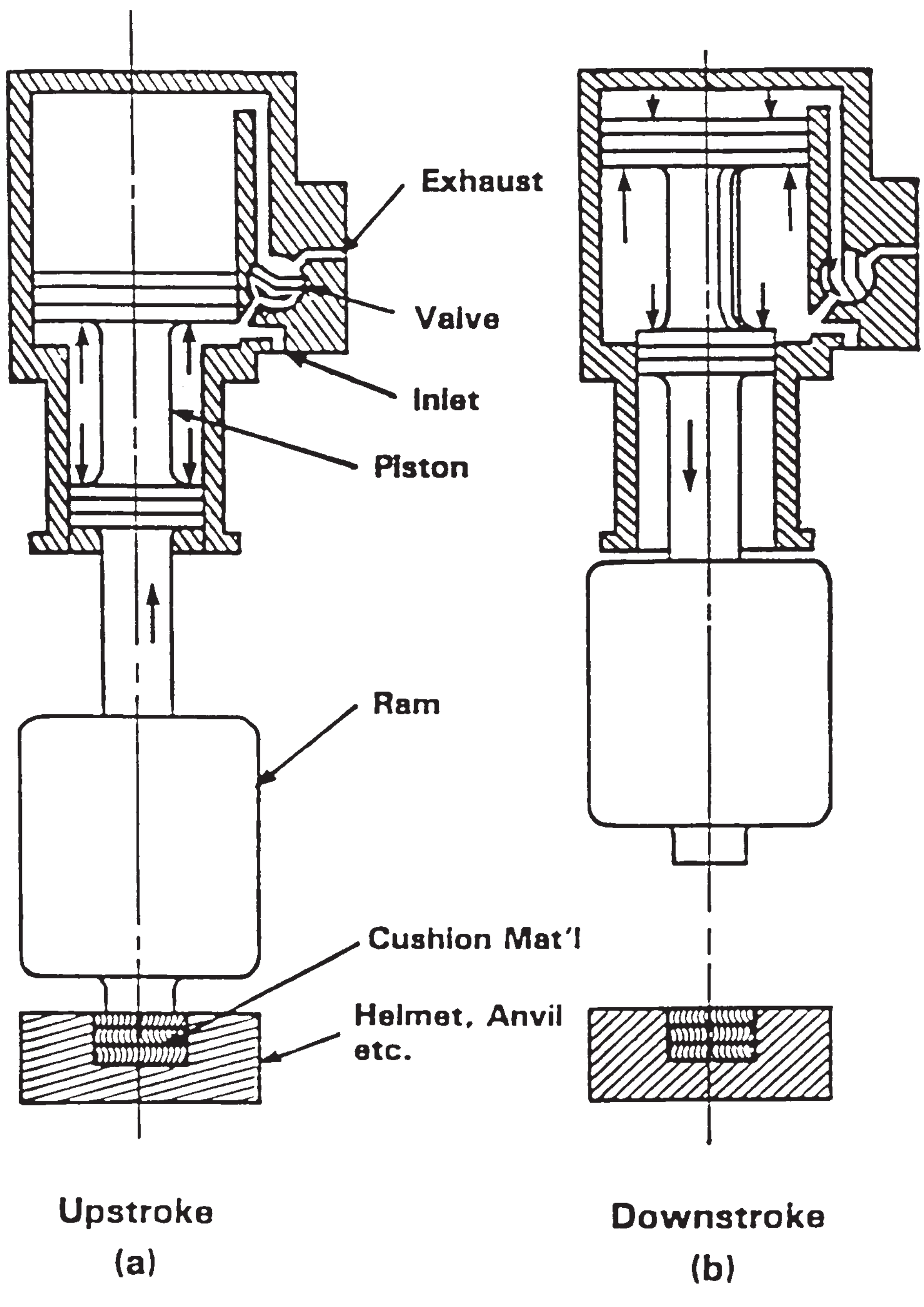


Figure 7-12: Differential Acting Steam/Air Hammer

Diesel Pile Hammers

In the early 1950's a new type of pile driving hammer was introduced - the Diesel Hammer. Basically, it is a rudimentary one cylinder diesel engine. It is fed from a fuel tank and pump mounted directly on the hammer, in contrast to air and steam hammers which require an external energy source. Simple to operate, diesel hammers are commonly used on most bridge contracts today.

Single Acting Diesel Hammers. The fundamental makeup and operation of all diesel hammers are similar. They consist of a cylinder-encased ram, an anvil block, a lubrication system, and a fuel injection system which regulates the same amount of fuel to each cycle. New models added a variable fuel metering system which can change the energy delivered by the ram, thereby making them more versatile for varying soil conditions. The energy imparted to the driven pile is developed from gravitational forces acting on the mass of the piston. Refer to Figure 7-13.

The operational cycle of the single acting diesel hammer is shown on Figure 7-14 and is described in the following paragraphs.

To start operations, a cable from the crane lifts the ram. At the top of the stroke, the lifting attachment is "tripped" and the ram allowed to drop.

The ram falls by virtue of its own weight and activates the cam on the fuel injector which injects a set amount of fuel into the cup-shaped head of the impact block. As soon as the falling ram passes the exhaust ports, air is trapped in the cylinder ahead of the ram, and compression begins. The rapidly increasing compression pushes the impact block (anvil) and the helmet immediately below it against the pile head prior to the blow.

Upon striking the impact block with its spherically shaped leading end, the ram drives the pile into the ground and, at the same time atomizes the fuel which then escapes into the annular combustion chamber. The highly compressed hot air ignites the atomized fuel particles and the ensuing two-way expansion of gases continue to push on the moving pile while simultaneously recoiling the ram.

As the upward flying ram clears the exhaust ports, the gases are exhausted and pressure equalization in the cylinder takes place. As the ram continues its upward travel, fresh air is sucked in through the ports, thoroughly scavenging and cooling the cylinder. The cam on the fuel injector returns to its original position allowing new fuel to enter the injector for the next working cycle. The operator may stop the hammer manually by pulling a trigger which deactivates the fuel supply.

The diesel hammer is difficult to keep operating when driving piles in soft material. As most of the energy is absorbed by movement of the pile downward, little remains to lift the ram high enough to create sufficient compression in the next downstroke to ignite the fuel. To resume operation, the ram must again be raised by the cable hoist.

It is generally accepted that the energy output of an open end diesel hammer is equal to the ram weight times the length of stroke. This combination ignores any component of the explosion which acts downward. In production pile driving, the stroke is a function of the driving resistance, the pile rebound, and the combustion chamber pressure. The combustion chamber pressure, in turn, will be affected by the general condition of the hammer as well as the fuel timing and the efficiency of combustion. Accordingly, manufacturer's energy ratings are based upon the hammer operating at refusal with almost all the energy of combustion developing the upward ram stroke.

Diesel hammers are very versatile. They may be connected to almost any leads. Since they do not require an additional energy source, such as steam or air, the size of the pile crew can be reduced. On occasion, piles are driven with as few as three workers, including the crane operator.

These hammers typically operate within a speed of 40 to 60 blows per minute and have strokes in excess of 10 feet. Although these hammers will drive any type of pile, their stroke is dependent on soil conditions. Hard driving in harder soils results in increasing stroke lengths, thus providing increasing hammer energies; while easy driving in softer soils results in lower stroke lengths and lower hammer energies.

Diesel hammers are noisy and they tend to spew oil and grease throughout. They also emit unsightly exhaust.

The Engineer should:

NO.	ITEM DESCRIPTION
1	Have the manufacturer's current specifications for the type and model of hammer being used.
2	Ensure all required parts of the hammer are intact and in good operating condition.
3	Be aware of the actual stroke of the hammer during driving and that it will vary depending on soil resistance.

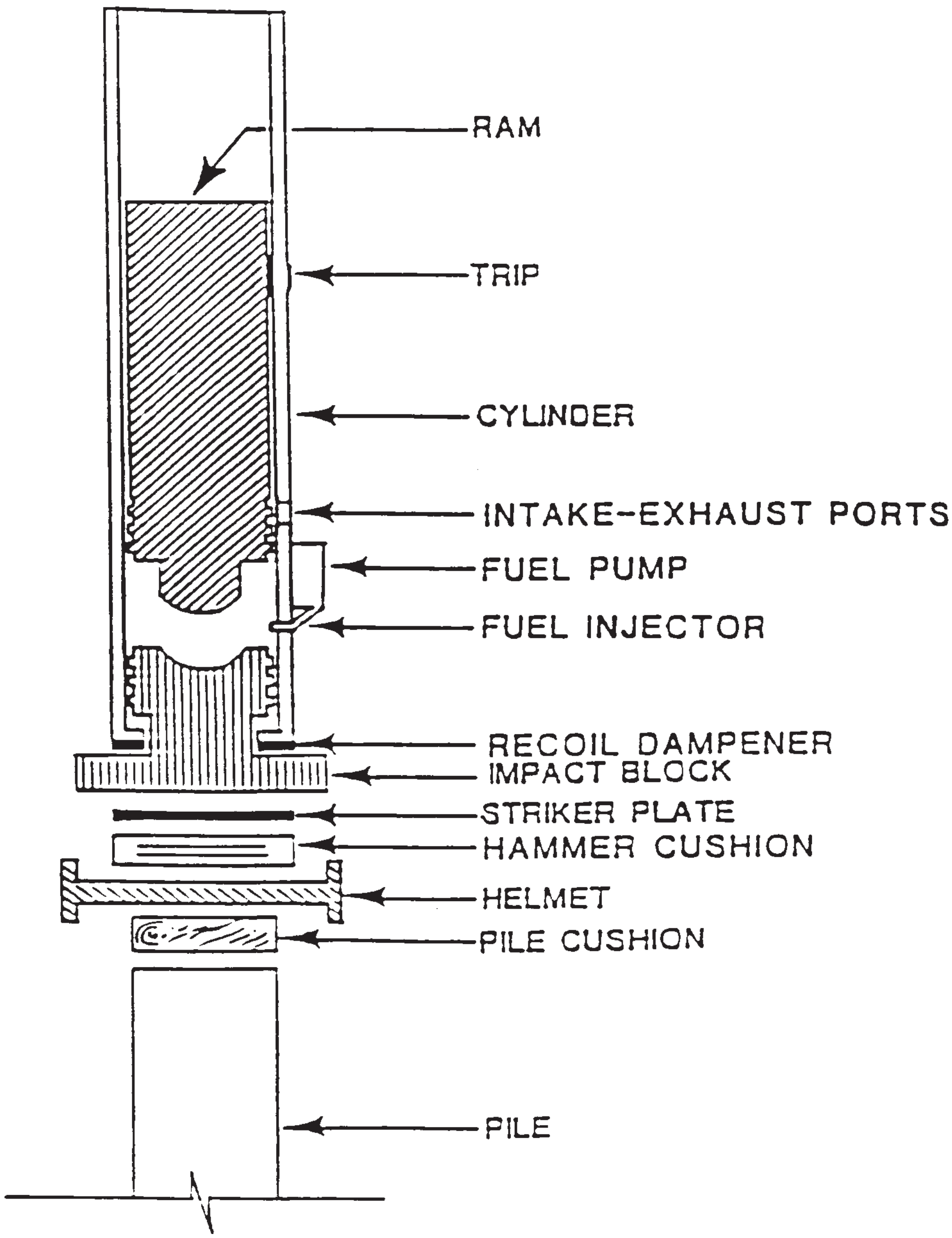


Figure 7-13: Single Acting Diesel Hammer

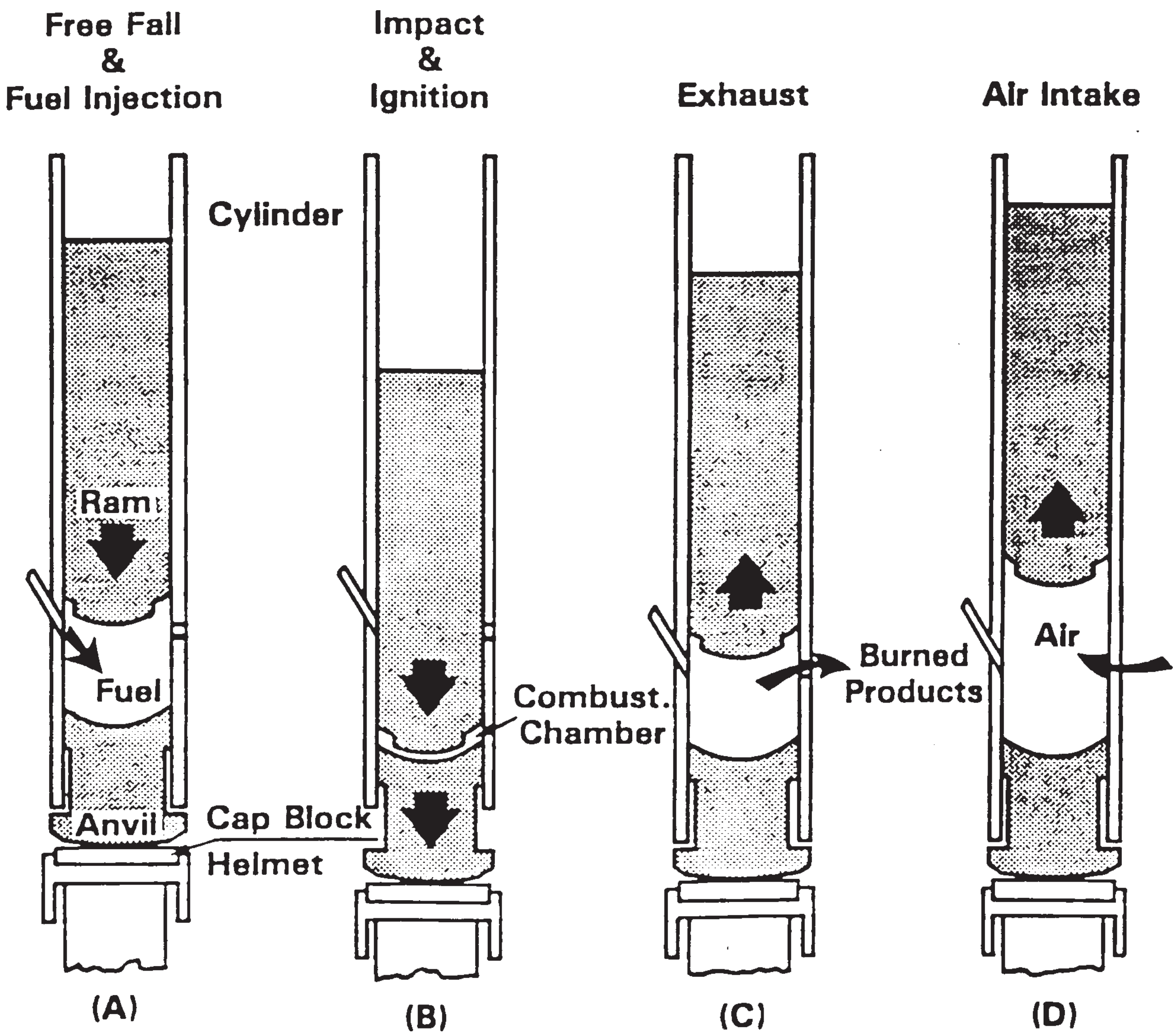


Figure 7-14: Operational Cycle for Single Acting Diesel Hammer

The Double Acting Diesel Hammer. The double acting diesel hammer is similar in its operations to other double acting hammers. The downward stroke is not just a function of gravity. The top of the cylinder is capped. As the ram nears the top of its upward stroke, the air is compressed in a "bounce chamber", which halts the upward flight of the ram. The downstroke energy is a function of both gravity and the internal pressure generated in the bounce chamber. The stroke of these hammers is around 3 to 4 feet and they operate at a much higher speed as compared to the single acting diesel hammer. Refer to Figure 7-15.

These hammers normally have a manually operated variable fuel injector, which is controlled by the crane operator. Unless the control is wide open, the energy delivered is of unknown quantity.

The rated energy of a closed end diesel hammer is computed from a formula incorporating the length of the free fall downstroke of the ram times the sum of its weight and changes in pressures and volumes of air in the bounce/scavenging chambers of the hammer.

Manufacturers have plotted the solutions to the formulae for each model of hammer for various pressure readings in the bounce chamber.

The Engineer should:

NO.	ITEM DESCRIPTION
1	Have the manufacturer's current specifications for the type and model of hammer being used.
2	Ensure all required parts of the hammer are intact and in good operating condition.
3	Ensure the energy chart made available by the manufacturer is the correct one for the model of hammer being used and that there has been a recent calibration or certification of the bounce chamber gauge.

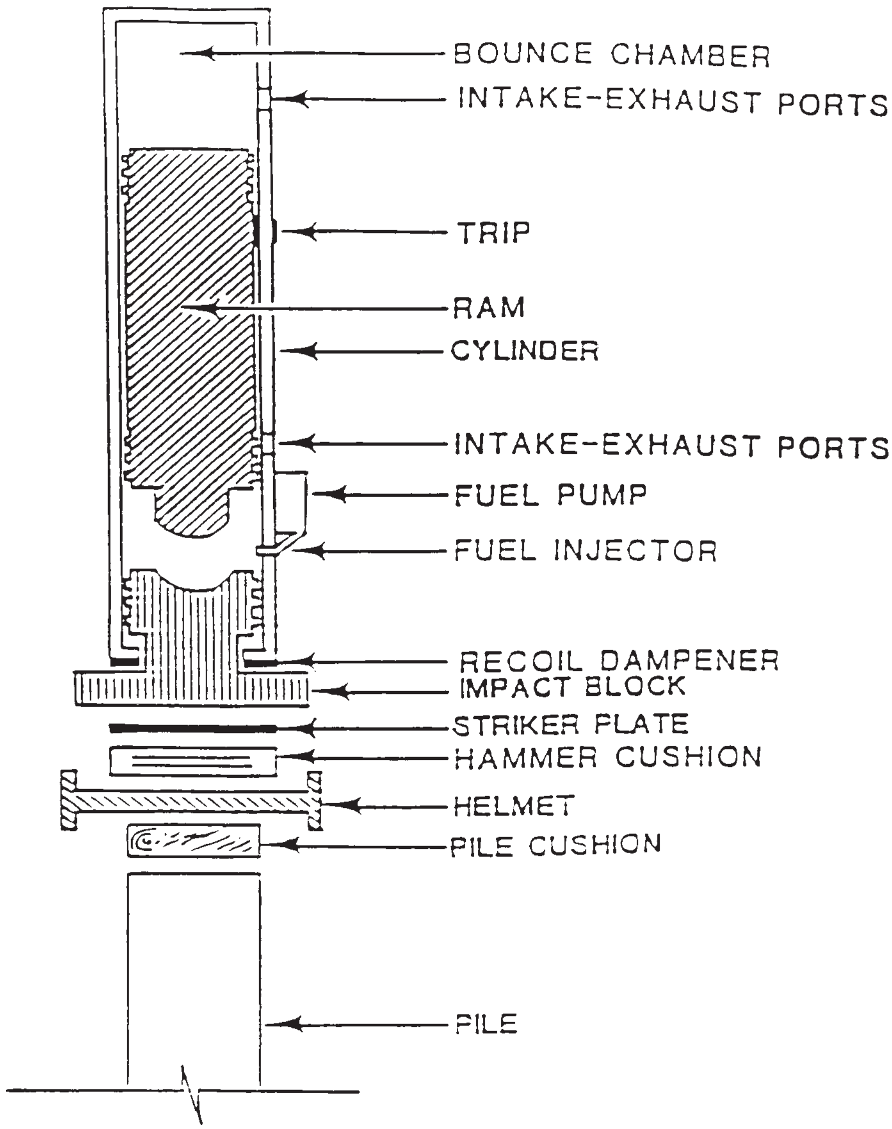


Figure 7-15: Double Acting Diesel Hammer

Vibratory Driver/Extractor

Because there is no way to determine the amount of energy delivered to the pile, Section 49-1.05 of the Standard Specifications prohibits the use of the vibratory hammer for driving permanent contract piles. However, it is frequently used by contractors for items of a temporary nature (i.e. placing and extracting sheet piles, etc.). They are also typically used as a means of extracting piles.

Vibratory pile drivers/extractors could be likened to ministroke, high blow rate hammers. However, the familiar vibratory pile drivers in standard use today do not contain linearly reciprocating weights or rams. Instead, they employ two balanced rotating weight sets, which are eccentric from their centers of rotation. Moving in opposite directions, they impart a vibration that is entirely vertical. This motion is transmitted to the pile through the hydraulic clamps of the driving head. The pile in turn transmits the vibratory action to the soil allowing the soil granules to be more readily displaced by the pile tip. The same action works even more effectively for extracting piles. Refer to Figure 7-16.

The effectiveness of a vibratory unit is dependent upon the interrelationship of the performance factors inherent to the unit. The larger the eccentric moment, the more potential vibratory force the driver possesses. In order to realize this potential force, the driver must operate with the proper frequency and amplitude.

Heavier piles mean higher vibratory weight which tends to reduce amplitude. So as piles get larger, it is necessary to use drivers with larger eccentric moments. The nonvibratory weight has the effect of extra weight pushing the pile downward.

Vibratory drivers are most effective in granular soil conditions, but recent developments and new techniques have also made them effective in more cohesive soils. They can handle a variety of piling, including steel sheets, steel pipe, concrete, timber, wide flange sections, "H" piles, as well as caissons. They do not create as much ground vibration as normal pile driving, thereby making the vibratory hammer desirable when possible damage to adjacent structures could occur.

The vibratory hammer has been permitted to drive a bearing pile to a point which would be a specified distance from expected final penetration. An accepted impact hammer has then been placed upon the pile to take it to acceptable bearing and final penetration in the normal fashion. Situations where this is of some use is where alignment of a pile is critical. The vibratory hammer allows the operator to minimize the rate of penetration of a pile, thereby allowing for more precise alignment of a pile as it gets started into the ground.

There have been comparisons made in the recent past indicating variances in bearing capacities of piles when comparing a pile driven to the same elevation with a vibratory hammer and one driven with an approved impact hammer. Items of interest and discussion include the "set" of the pile and the disturbance of the soil mass. When a request is made to use a vibratory hammer to start a pile, the Engineer should:

NO.	ITEM DESCRIPTION
1	Be aware of specific pile requirements and limitations as might be stated in the Special Provisions and the Standard Specifications.
2	Discuss the proposal with the Bridge Construction Engineer, the Project Designer, and the Engineering Geologist.

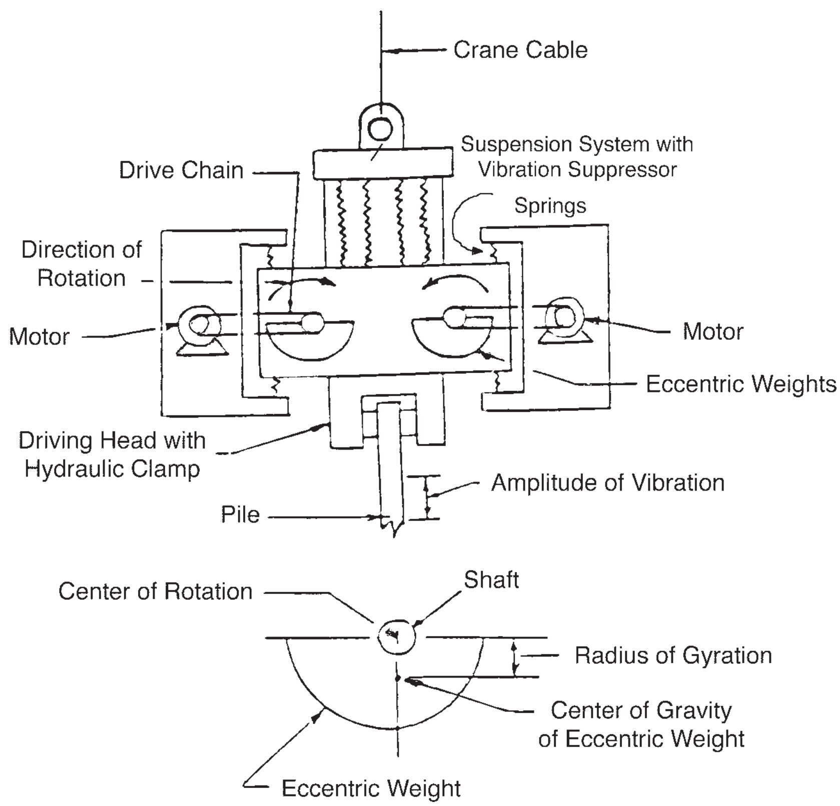


Figure 7-16: Vibratory Driver/Extractor

Hydraulic Hammers

A hydraulic hammer is one that incorporates the use of an external energy source to lift the hammer to the top of its stroke. For the single acting hydraulic hammer, the actual energy induced into the pile is developed by the free-falling piston, much the same power stroke as a drop hammer or a single acting diesel hammer. The rated energy for the differential acting hydraulic hammer is found by similar means as other differential acting hammers.

Some will say that a differential acting hydraulic hammer is no different than any other differential hammer.

One particular hydraulic hammer manufacturer utilizes a ram made of composite material. In this case the ram is made of lead wrapped in steel. The stroke is relatively short for a single acting hammer, generally about 4 feet. The theory behind this particular hammer is that the lead ram produces a blow with a longer impact duration. This longer impact duration produces a compression wave which is low in amplitude and long in duration. It is thought that this type of blow is more efficient in terms of delivering driving energy to the tip of the pile (relative to a light weight hammer with a longer stroke).

The hydraulic hammer has a variable stroke, which is readily controlled from a control box. With the control box the stroke can be varied, finitely (reported to be in the centimeter range), such that the stroke can be optimized to the point of matching the dynamic spring constant of the hammer and pile. Manufacturers have stated that the ability to vary the stroke and frequency is what makes the difference.

The general theory behind the hammer is as follows. Every ram body, depending on material and cross sectional area, has its own dynamic spring constant. Likewise, each pile, based on different materials and sizes, has its own dynamic spring constant. The dynamic spring constant is also known as the acoustic impedance. It is believed that, the closer the dynamic spring constant is between the pile and the hammer, the higher the energy transmission will be through the pile and the lower the internal stress will be in the pile, since all the hammer energy goes into penetration of the pile. If the hammer impedance is the same as the pile impedance, a pile cushion would be unnecessary and driving would be optimized.

The manufacturers of these types of hammers claim the following:

NO.	ITEM DESCRIPTION
1	Hammer efficiencies in the range of 80% to 98%, while claiming diesel hammers to have an efficiency in the range of 30% to 40%.
2	Due to the increased efficiency of the hammers and because more energy is transmitted through the hammer, there is less internal stress of the pile, less pile damage, etc.
3	They claim the operation to be quieter than the typical diesel hammer.
4	The typical exhaust of the diesel hammer is eliminated, since only the motor driving the hydraulics is the source of exhaust.
5	Avoids diesel hammer problems of soft ground starting and operating in extreme climates.

A hydraulic hammer has been tested on a Caltrans project. The hammer was tested in conjunction with a single acting diesel hammer. Piles were driven with both hammers. Bearing of the hydraulic driven piles were verified by means of a retap, using the diesel hammer.

The results indicated that the diesel hammer required twice as much energy to move the pile one foot when compared with the energy of the hydraulic hammer.

Currently the hydraulic hammer is not considered an approved impact hammer for determining the bearing value of a driven pile. The problem with the use of such hammers is the verification of energy induced. The question remaining is to the relationship of the hydraulic hammer versus the Engineering News-Record (ENR) formula.

Although we do not allow the hydraulic hammer to be used with the ENR formula, the Wave Equation Analysis has been used on this type of hammer successfully.

General Hammer Information

Section 49-1.05 of the *Standard Specifications* requires that the Contractor furnish an approved hammer having sufficient energy to drive piles at a penetration rate of not less than $^1/_8$-inch per blow at the required bearing value. In effect, this specification places a lower limit on the hammer size because hammer size, in most cases, is related to energy. An upper limit is not specified.

Economics often dictate hammer size selection by contractors. Large hammers with increased energy will reduce driving time. They will also help achieve penetration where hard driving is encountered, thus enabling completion of the work without the need of supplemental measures (jetting or predrilling). On the other hand, heavy hammers require heavy leads and heavy cranes; the result being decreased mobility and increased equipment costs. Ideally the Contractor will come up with a "mid-range" selection. Another consideration is that a larger hammer will deliver more usable energy to the pile. Hence, the probability of pile damage (heavy spalling or other) is increased as hammer size is increased. Ram impact velocity is another important factor. In general, a large ram weight with a short stroke and low velocity at impact will not produce the magnitude of pile stress that a light ram with a long stroke and high velocity will induce. At constant driving energy, the driving stress on the pile will decrease as the ram weight increases.

Bearing Capacity

In lieu of a static load test, the typical method for determining load bearing capacity of a pile depends on knowledge of the energy used to drive the pile. This was stated earlier in the chapter by saying, "not only is the pile hammer the production tool for the Contractor, it is also a measuring device for the Engineer". Various methods and procedures are available when using the known driving energy to determine the bearing capacity of the pile. These procedures can be categorized into three areas: (1) Pile driving formulas, (2) wave equation analysis of pile driving, and (3) dynamic pile driving analysis.

Pile driving formulas all utilize the energy delivered per blow, the resistance to the movement of the pile per blow, pile penetration, and some acknowledgement of the unknown produced by all the components which act to drive the pile. All of the driving formulas make use of the conservation of energy theory:

(HAMMER ENERGY) – (ENERGY LOSSES) = (WORK PERFORMED)

Soil resistance multiplied by pile penetration represents work performed, hammer stroke multiplied by ram weight represents hammer energy, and various factors and/or constants in driving formulas represent energy losses in the piling system. The desired objective is to account for the most significant energy losses so that soil resistance can be estimated.

Some of the energy losses associated with pile driving are hammer combustion and mechanical inefficiency, hammer and pile cushion restitution, dynamic soil resistance and pile flexibility. No pile driving formula accounts for all energy losses, and the major difference between formulas is which losses each considers.

There are many different (at least 450) pile driving formulas, the more notable of these being the Gates, Hiley, Pacific Coast Uniform Building Code, Janbu, and the ENR. Refer to Appendix E for examples.

Section 49-1.08 of the *Standard Specifications* requires that the bearing value of driven piles be determined using the ENR formula.

This formula was developed prior to the year 1895 by Arthur Mellon Wellington, the general manager and part owner of Engineering News-Record. Wellington developed it for timber piles driven with a drop hammer. The formula was modified at a later date with the advent of steel and concrete piles and more sophisticated hammers. Both the original and the updated versions are given in the *Standard Specifications*. The ENR formula is the most commonly used in this country.

Section 49-1.08 of the *Standard Specifications* gives two different variations of the ENR formula. One of these is used for drop hammers and the other is used for single or double acting hammers or diesel hammers (Refer to Appendix E for a derivation). Of these two, the most commonly used is the diesel hammer formula and is as follows:

$$P = \frac{2E}{s + 0.1}$$

where:

P = safe load in pounds
E = manufacturer's rating for foot-pounds energy developed by the hammer
s = penetration per blow in inches

Inspection of the diesel hammer formula shows that it is an energy conservation equation with an additional 0.1 inch term and a reduction factor of 6. The intention of the 0.1 inch term is to account for elastic rebound and to encompass energy losses in the piling system. The reduction factor of 6 relates the result of the ENR formula to a safe (working stress) load. Ideally, this would mean a safety factor of 6. Comparisons of safe pile loads predicted with the ENR formula and measured capacities from statically load-tested piles have shown the factor of safety to vary greatly. Actual factors of safety have been shown to range between 0.8 and 30 when this formula is used.

Why do we use the ENR formula in the field?

1. Simplicity – Relatively short calculation needed for determination.
2. Simplicity – Certain factors in other formulas are subjective in nature and could be difficult to determine.
3. Simplicity – Subjective evaluations required by other formulas could precipitate contractual problems.
4. Dependability – Over the years, our experience with the ENR formula has been good.

It must be remembered that driving formulas are simply tools used to aid the evaluation of a pile's capacity. Experience and engineering judgment are of immense value in this work.

Field measurements of bearing capacity on large displacement piles, in excess of 100 Tons, have shown that the ENR formula is not necessarily reliable. It is believed that a significant amount of the driving energy is being used just to get the large pile mass moving.

Although the Standard Specifications do require the use of the ENR equation, research is showing that the use of the wave equation analysis provides a more reliable correlation to static pile load test results than does the ENR formula. The enhanced accuracy is achieved by providing a more detailed accounting of energy losses.

Dynamic Analysis by Wave Equation

Wave equation analysis of a pile driving operation is a one dimensional finite difference method which models the transmission of a hammer's impact wave down a pile and into the soil. The method has been around for more than two decades. Several versions of the program are available, some of which can be run on a personal computer. One of the most widely known versions is called Wave Equation Analysis of Piles (WEAP).

What a wave equation analysis does is model the pile and the driving system as a series of masses and springs. The relative sizes of the springs and masses depends on the actual pile and driving system characteristics. The soil is represented by a series of elastic plastic springs and linear dashpots. After modeling the pile, the driving system and the soil, the ram elements are given a velocity equal to the hammer impact velocity and a dynamic analysis is performed.

The wave type analysis is relatively new to Caltrans. To date it has varying uses. Among them are: (1) Driveability Study, (2) Hammer Acceptance Study, and (3) Acceptance Curves.

Driveability Study. In the Driveability Study, the wave equation analysis would be used in the design phase. For this study, the user (as of now this would be someone from the Office of Structural Foundations) will input a driving system model. The input information consists of a typical hammer, cushion, soil characteristics, and length of pile; all of which is generally referred to as the pile driving system.

The output of the analysis will tell the user if the pile is driveable. The output information will include the internal stresses of the pile as it travels through the varying strata and as it approaches a particular tip elevation. The output will also give driving rates for specific hammers at specific elevations. The hammer input information is within a range for a "typical hammer" that might be used. The soil information is based on information gained from the Log of Test Borings for the particular site. All of the above input information is refined for further uses in the wave equation. As a summary for this use, the Driveability Study is one which is used by the Project Designer to help in choosing a foundation type.

Hammer Acceptance Study. The Hammer Acceptance Study would typically be done after the contract is bid. This type of study requires information regarding all of the components that a Contractor would propose to use for the installation of contract piles. This information would be submitted to the user. The user inputs all of the submitted information and, from the output of the program, determines if the hammer can drive the pile, what the driving rate would be, and the user will be able to predict the internal stresses of the driven pile. From this information, the Engineer can decide if the Contractor's hammer will drive the pile to tip without overstressing the pile. From the output information, the Contractor might discover that the chosen hammer would not be efficient to use in a given situation. The Contractor might choose to use a different hammer that might be more efficient. The new hammer's characteristics would be re-input and the output would be studied for the previous stated reasons.

Acceptance Curve Study. For the Acceptance Curve study, the previous two studies are completed. After the Contractor's hammer is known, modeled and accepted, a pile would be driven in the field. The driving of this pile would be monitored using Pile Dynamic Analysis (PDA) equipment, which records a dynamic analysis using monitors attached to the driven pile. After the pile is driven a static load test might be performed. Using information gained from the PDA, the static load test and information from other analysis programs, the input information for the WAVE analysis is refined to more closely model the hammer and soil system characteristics. From the refined input, the WAVE output can be used to develop acceptance curves, based on stroke, blow count and driving rate relative to a specific footing location. The output would be used by the Engineer in the field to determine acceptance of a driven pile. Refer to Appendix E for samples of acceptance curves.

The previous method, as outlined, is quite comprehensive. This type of analysis would normally be done only on a large project. Where this type of analysis has proven useful is as follows. Piles were driven in Bay Mud type material. Take-up curves were developed using the static load tests on test piles over a given period of time. These take-up curves measured the gain in soil resistance realized over time. All of the information was put into a WAVE analysis. The output predicted what the blow rate and stroke should be at the time of driving for a particular driving system. What happened in the field is that the Engineer accepted a pile driven to specific blow rates and stroke length. The accepted blow rate and stroke were determined using the knowledge of the increased bearing value, over time, characteristics of the piles. If the piles had been driven using only the ENR formula, the Contractor might still be driving them. The WAVE program allowed the user to utilize the take-up information to model the soil characteristics more accurately. In this case it save the owner (Caltrans) lots of money.

The advantage of wave equation analysis over pile driving formulas is that it accounts for the physical characteristics of the pile driving system and soil resistance. A WEAP analysis has its greatest advantage over driving formulas where the pile is driven through layers of soft soil and a significant portion of the pile capacity is derived from skin friction. Where a pile is driven into firm strata or bedrock, the pile often derives most of its static capacity from end bearing. For predominantly end bearing piles, WEAP analyses for the purpose of generating penetration/capacity relationships may not be necessary. Nevertheless, a WEAP analysis has the capability of being able to predict potential pile overstressing during hard driving.

Where a pile is advanced through material which can not be relied on for contributing skin resistance, WEAP analysis provides a means of establishing pile driving criteria consistent with design procedures. Situations where this is a concern include river channels where scourable material is present, and sites having down-drag or negative skin friction forces generated by soil consolidation. Because the ENR formula predicts safe rather than ultimate capacity, and has an unknown safety factor, it does not provide a logical means of considering the driving resistance contributed by these layers. WEAP is based on ultimate pile capacity and thereby provides this capability.

Manufacturer's Energy Ratings

Generally each manufacturer publishes a catalog or brochure for their hammer. Within the printed information they typically will outline operating specifications, including any specific equipment which will be required. Specifications of importance to those involved in monitoring driven pile installation are ram weight, stroke, blows per minute, energy rates and required steam or air pressure.

Accurate determination of a given hammer's available energy is difficult. Manufacturers calculate hammer energy differently. McKiernan-Terry uses ram weight times stroke. At one time, Delmag calculated a hammer's energy as a function of the amount of fuel injected. They now use the weight of the hammer times the stroke. Link-Belt considers stroke, fuel, and the effect of the bounce chamber. Keep in mind that a hammer's rated maximum energy is typically rated when the pile hammer is operating at or near refusal.

The Standard Specifications state that "E" is the manufacturer's rating in foot-pounds of energy developed by the hammer. It is used in the ENR formula. When single acting diesel hammers are used, it is necessary to determine energy by multiplying ram weight times the actual stroke. This requires field observation of the actual stroke. This approach is both simple, conservative and almost universally accepted. The manufacturer's given energy rating should not be used "blindly" in the ENR equation. Energy output should be verified by measuring the stroke of single acting diesel hammers or by comparing the operations of the hammer with the manufacturer's operating specifications.

One sometimes hears discussion about the "efficiency of a hammer". The efficiency is merely the net kinetic energy normally delivered by a particular hammer to the pile cap block divided by the potential energy of the hammer at the beginning of its stroke; or, in other words, the percentage of the total potential hammer energy available at the top of the stroke which is actually delivered by the ram of the hammer at impact. As has been mentioned above, engineers and inspectors use the rated energy of hammers as an indication of the driving capability of the hammer. Manufacturers do not specify the amount of kinetic energy delivered by a hammer at the head of the pile after undergoing energy losses. These losses occur in transfer of energy through the driving system. Because all pile load bearing formula are applied with safety factors, these energy losses, common to all hammers, are usually accounted for in the load bearing formulas or are ignored. What you, as the Engineer, must then ensure is that the accepted hammer on the job is operating properly and is capable of producing the manufacturer's "rated energy" (or potential energy, at the top of its stroke).

There are many factors that contribute to the loss of efficiency, such as wear, improper adjustment of valve gear, poor lubrication, unusually long hoses, minor hose leaks, binding in guides, and minor drops in steam or air pressure. All of the preceding illustrates the necessity for the Engineer to have a working knowledge of hammer operations.

Material presented in this manual and material found in other technical publications will supplement this knowledge. However, there is no substitute for field experience. The Engineer is well advised to look into the mechanical aspects of the pile operation when the Contractor starts assembling the equipment and driving begins.

Even though it is usually very small, the Engineer should also be aware of the energy adjustment needed when battered piles are driven. Since the path of the ram will follow the slope of the pile, the stroke used to compute delivered energy must be adjusted to reflect the vertical fall of the ram. This is simple to determine for single acting air, steam or diesel hammers. For example, a 70 Ton pile driven with a Delmag 30 hammer will normally require 14 blows per foot. If the pile is driven on a 1:3 batter the minimum blow count would be increased to 15 blows per foot ((3.162/3) ¥ 14). Refer to Appendix E for an example of this.

A similar adjustment must be made for double acting and differential hammers. However, in determining this, compensate only for that portion of the energy attributed to the free fall of the ram. Energy delivered by differential action or pressure imparted on the downward stroke should remain constant.

Preparing to Drive Piles

Pile driving techniques (including solutions to problems) are normally developed with time and experience. It is the intent here to provide some insight into the areas where problems do exist and where they can develop, so that as many as possible can be eliminated or resolved before they occur.

The following material is essentially a check list of what the Engineer should look for before driving begins and while driving is underway. This list is by no means complete as new and different problems will develop with each and every project.

Prior to going out in the field:

NO.	ITEM DESCRIPTION
1	Review the Plans, Special Provisions and Standard Specifications for requirements on pile type, required bearing and penetration, predrilling depths (critical with tension piles as well as compression piles), tip protection or pile lugs and limitations on hammer types or other specific limitations or requirements.
2	Check for Form TL-29, "Release of Materials."
3	Check for welder certification requirements.
4	Prepare the pile layout sheet.
5	Prepare the pile log forms.
6	Advance preparation of a chart, table or graph which correlates the blow count, stroke, blow rate, etc., to the bearing value is suggested for each hammer. An example is included in Appendix E. Verify the hammer is an approved hammer in accordance with the requirements of Bridge Construction Memo 130-2.0 and is able to develop sufficient energy to drive the piles at a penetration rate of not less than $^1/_8$-inch per blow at the required bearing value. Refer to the "Verification of Hammer Energy" section later in this chapter.
7	Review the mechanics of the hammer type to be used for further verification of components in the field.
8	Obtain the necessary safety equipment (Refer to the "Safety" section later in this chapter) and inspection tools (tape measure, paint, stop watch, etc.)

Once out in the field, prior to start up of driving:

NO.	ITEM DESCRIPTION
1	Confirm pile layout and batter requirements. The Contractor is to locate the position of the piles in the footing. The Engineer is to check the layout only. Do not lay out piles for the Contractor.
2	Confirm pile materials, tips and lugs. Refer to the "Materials Checklist" later in this chapter.
3	Confirm the hammer type. If the hammer has a variable energy setting, check the setting to ensure the proper energy will be obtained. Some of the newer diesel hammers have four settings giving a range of 46% to 100% maximum energy.
4	Verify the reference elevation.
5	Layout and mark piles for logging. Mark additional reference points near the anticipated tip elevations so that monitoring can take place at smaller increments.
6	Locate a good place to inspect operations. Notify the pile foreman of location and signals to be used.

When driving starts:

NO.	ITEM DESCRIPTION
1	Verify the pile location at the start of driving.
2	Verify plumbness or batter of the pile at the start of and during driving.
3	Monitor and log the blow count, stroke and penetration (Refer to the "Logging of Piles" section later in this chapter).
4	Stop driving at proper bearing and penetration.

After completion of driving piles:

NO.	ITEM DESCRIPTION
1	Verify proper pile cutoff.
2	Prepare copies of pile logs to be sent to the Office of Structure Construction in Sacramento in accordance with Bridge Construction Memo 3-7.0.

Verification of Hammer Energy

Some method of field verification of driving energy must be available to the Engineer. For single acting diesel, steam or air hammers, the simplest method is to measure the stroke of the hammer and multiply this by the weight of the ram. While some manufacturers disagree with this method, this remains the best method available in the field. For diesel hammers, measure the depth of ram below the top of the cylinder before driving and add the height of ram visible during driving. This may require the painting of one foot marks on the trip carriage.

Some hammers have rams with identifiable rings which are visible during driving. The location of the rings normally is shown on the manufacturer's brochure.

The maximum rated stroke for maximum rated energy for many hammers is given in Bridge Construction Memo 130-2.0.

Another method of determining the actual ram stroke of an open end diesel hammer is accomplished by measuring the ram stroke from the blow rate. The equation involved with this method is sometimes called the Saximeter equation. Saximeter is a trade name for a device used for remote measuring of the stroke of an open end diesel hammer or the measurement of the hammer speed. An example is also available in Appendix E.

For Air and Steam hammers, check the boiler or air capacity of the outside energy sources. This should be equal to or greater than that specified by the hammer manufacturer. Gages should also be available to check required steam and air pressures.

Check for proper hose size of steam and air hammers. The hoses should comply with the manufacturer's specifications. All hoses should be in good condition (no leaks).

Materials Checklist

Pipe Piles

CHECK ITEM	CHECK DESCRIPTION
1	Check for proper diameter and shell thickness. Paint one-foot marks and lengths on the piles. The Contractor may assist in this.
2	Check welded joints for any sign of improper welding. If piles are to be spliced, the welder must be prequalified. Refer to Section 49-5.02 of the *Standard Specifications*.

Precast Concrete Piles

CHECK ITEM	CHECK DESCRIPTION
1	Check for damage, cracks, chips, etc. Check the date the pile was cast. This date is written along with the release number directly on the surface of the pile. Section 49-1.07 of the *Standard Specifications* requires that piles be at least 14 days old before driving.
2	Lifting anchors for Class C piles are to be removed to a depth of one inch and the hole filled with epoxy. Piles without Class C designation shall have the anchors removed for the portion of pile above the final ground line. Section 49-3.01 of the *Standard Specifications* covers this subject.

Discuss with the Contractor the type and method of rigging planned to lift the precast/ prestressed concrete piles. The Contractor is to provide the necessary equipment so as to avoid appreciable bending of the pile or cracking of the concrete. If the Contractor materially damages the pile, the pile must be replaced at the Contractor's expense (Refer to Section 49-3.03 of the *Standard Specifications*).

Check the lifting procedure to ensure that the pile is not overstressed at anytime during picking.

$$\text{Allowable Stress} = 5\sqrt{f_c'}\ \text{PSI tension}$$

Measure piles and paint the necessary one foot marks so blow counts can be determined. Check the ends of the piles. Prestressing steel should be flush with the pile head. The head of the pile should be square.

With concrete piles, make sure the cushion blocks are maintained in good condition. If the driving is hard, they may have to be changed once or twice per pile.

Steel Piles

If the piles are to be spliced, the Contractor must have a prequalified welder do the work. If the welder has been performing similar type work on other Caltrans jobs and 12 months have not elapsed since this work, the welder does not have to run a prequalification test. Verification of the welder's work record can be obtained by calling the Office of Materials Engineering and Testing Services (METS) in Sacramento with the welder's name and social security number.

Some welders who are not listed with METS will have qualification tests that were performed by a private testing laboratory. Prequalification can be accomplished in this instance by forwarding a copy of the test reports to the nearest Transportation Laboratory office where they will verify the welder's qualifications.

If the welder does not meet either of the above requirements, a prequalification test will have to be made. A review of the ANSI/AASHTO/AWS D1.1 Welding Code will outline the requirements.

It is obvious that all of the aforementioned takes time. Hence, it is extremely important that determination of welder qualification be made as early as possible. It should also be noted that once the welding work has been completed on the job by the certified welder, the Engineer should forward a copy of the work record to the Office of Materials Engineering and Testing Services. This will help to maintain current records and hopefully save someone some time later on. Also keep in mind that just because a person holds a welding certification, it does not mean you do not have to look at the welding work.

Early contact with Transportation Laboratory representatives in either Los Angeles, Berkeley, or Sacramento is encouraged as they can be very helpful. Reference should also be made to Section 180 of the *Bridge Construction Records and Procedures* manual.

Timber Piles

Check the butt and tip diameters to ensure compliance with Section 49-2.01 of the *Standard Specifications*. Treated timber piles shall be driven within 6 months after treatment.

Piles shall have protective steel straps at 10-foot centers. Three additional straps are placed at the tip and two at the butt. Straps are to be approximately 1¼ inches wide and 0.3 inch in nominal thickness per Section 49-2.03 of the *Standard Specifications*.

The Contractor is also required to restrain the pile during driving from lateral movement at intervals not exceeding 20 feet measured between the head and the ground surface. Make sure the Contractor is equipped for this.

Logging of Piles

It is Office of Structure Construction policy to log at least one pile, in it's entirety, per footing. There are advantages to doing a more comprehensive logging of the piles. One situation is when, during easy driving, the piles are not achieving the necessary blow counts at specified tip. The Contractor will request to retap them later. A good log of the piles within the footing will help the Engineer to determine how many piles might require a retap to prove bearing. If all the piles drove in a similar manner, it might be possible to retap as few as 10% of the piles that did not originally achieve bearing. If the piles all drove differently, a retap of all of the piles may be required. The following is a discussion of factors affecting pile log data.

Typically when driving begins, the driving resistance of the pile is very low. The stroke of the hammer will be proportional to this pile resistance (low resistance equals low rebound energy). As a result, the energy delivered to the pile will be different from the manufacturer's rated energy value. Keeping careful track of blows per foot and actual stroke is necessary. If this difference is not taken into account, the log will be misleading when the values are put in the ENR formula and bearing values are computed at various depths of driving. This procedure should be followed all the way to the final tip penetration.

With double acting steam or air hammers, check the gages for proper pressure during the driving operation. In addition to measuring the actual stroke, it is important that the blow rate be verified.

Underwater and ''closed'' system hammers are difficult to inspect and can be throttled by the operator. The full open position should be used to obtain maximum energy. When logging piles or determining final blow count, pick a fixed reference point as close to the pile as practical. This can be accomplished several ways: (1) Mark the lower part of the leads with one foot marks and observe passage of a fixed point of the pile, or (2) Mark the pile with one foot marks and note the blows passing a fixed point near the pile (leads, reference point, lath driven near the pile, water surface or other). Site conditions often dictate how this is done, so improvise as necessary. Modifications must also be made to obtain blow counts over smaller increments.

If a precast pile is undergoing hard driving and suddenly experiences a sudden drop or movement, this could indicate a fracture of the pile below ground. Driving should stop and an investigation of the soundness of the pile should be made. Piles which are damaged should be extracted. However, this is not always possible. Frequently this problem is solved by driving a ''replacement'' pile next to the rejected one. When this is done the effect of the change could impact the footing design.

When driving hollow pipe piles in water, be aware of the water level in the pile. Water hammer developed during driving could split the pile. This may require that the Contractor seat the pile and stop driving long enough to pump it dry before continuing the drive. Beware if water gets close to the pile top! Another problem with pipe piles has to do with what is called a soil plug. When driving hollow piles, there is a tendency for the soil to plug within the pile as it is being driven. This is common in cohesive materials. When this does occur the pile will drive as if it is a displacement pile. There are many implications if this happens. Among the possibilities include the possible overstressing of a pile as well as misleading blow counts.

Driving Problems

Problems with driving can vary in nature and cause. In general there are three categories of problems: (1) hard driving, (2) easy driving, and (3) pile alignment. The causes typically are either the soil is too hard or soft, the type of hammer used is inappropriate for the soils encountered, or the pile type being used is inappropriate. The following is an outline of various driving problems that can be encountered. The types of problems described are, by no means, a complete listing of all possible problems.

Hard Driving

Hard driving occurs when either the soil is too dense to accept the pile or the hammer cannot produce enough energy to drive the pile. A review of the Log of Test Borings may be an indication of the type of driving that can be expected. Current specifications provide measures to be used when these conditions exist.

Section 49-1.05 of the *Standard Specifications* states: "When necessary to obtain the specified penetration and when authorized by the Engineer, the Contractor may supply and operate one or more water jets and pumps, or furnish the necessary drilling apparatus and drill holes not greater than the least dimension of the piles to the proper depth and drive the piles therein."

When it appears that driving through dense or rocky soil could damage the tips of driven piles, the Standard Specifications require the Contractor to provide special driving tips, heavier pile sections, or other measures as approved by the Engineer, to assist in driving a pile through a hard layer of material.

The Engineer should consult with the Engineering Geologist if hard driving is a problem and the Contractor is considering either jetting or predrilling. There may be limitations on the use of jetting. Predrilling and predrilling depths should also be discussed since there may be certain limitations.

Care must be exercised when jetting is used. Two methods are generally employed: (1) pre-jetting, and (2) side jetting. In terms of controlling pile alignment pre-jetting is best. A pilot hole is simply jetted to the desired depth. After the jet pipe is withdrawn the pile is immediately inserted in the hole and driven. With side jetting the jet pipe is inserted into the ground adjacent to the pile and the jetting and driving take place concurrently. Care must be taken when this is done with a single jet as the pile tip will tend to move off line in the direction of the jetted side.

Larger piles are frequently side jetted with multiple pipe systems. These systems can be located outside the pile or within the annular space of hollow piles. In addition, the pipe arrangement of multiple pipe systems is usually symmetrical, thus enabling better control of pile alignment.

Spudding is another method used to assist penetration. This is where an "H" pile or similar section is driven to break or cut through hard material. Contract piles should not be used for spudding unless the pile has been specifically designed for this type of action.

The term "hard driving" is subject to much individual interpretation and there are no set guidelines in the specifications, save certain requirements for timber piles. When the blow count for timber piles reaches specified limits, the Contractor is required to take prescribed measures of assistance. This could include predrilling, jetting or a change to a larger low velocity hammer.

In the case of steel or concrete piles, no measures are specified to mitigate hard driving at predetermined blow count levels. However, the Contractor is required to employ the measures described above to obtain the required penetration and is also required to use equipment which will not result in damage to the pile.

Physical damage to the pile, even when it is below ground, is fairly easy to determine. Impending damage and/or high driving stresses are not as easy to pinpoint. In situations of high driving resistance, the Engineer is well advised to investigate pile stresses. In the book *Pile Foundations*, Chellis covers this subject fairly well and it is recommended as reference material.

The subject of pile refusal has to be included in discussions about hard driving. Unfortunately, there are nearly as many definitions for the term "refusal" as there are those who attempt to define it. Some popular interpretations range from: (1) twice the required blow count, (2) 10 or more blows per inch, or (3) no penetration of the pile under maximum driving energy. Some contractors would like us to think of refusal as something in the double the required blow count range. These contractors also feel that Caltrans labors under the concept of refusal as that point just prior to self destruction of the hammer.

Is any specific definition valid? Not really. Refusal should be viewed as very little or no penetration of the pile with a reasonable amount of delivered hammer energy. In determining a reasonable amount of hammer energy one should be satisfied that the hammer is (1) operating efficiently, (2) operating at maximum energy, and (3) sized properly.

One should keep in mind that proper hammer sizing is not accomplished simply by meeting the minimum energy requirement given in the *Standard Specifications*. It is important to be aware of the relative weights of the hammer and the pile. Certain "light" hammers will meet our minimum penetration or energy requirements and, at the same time, they can be dwarfed by the size of the pile. This can result in a situation analogous to driving a large spike with a tack hammer.

Hard driving can also be the result of a pressure bulb developed near the pile tip. This can occur in saturated sandy materials. Driving in stages is a suggested remedy for this situation.

Soil consolidation due to cluster driving of displacement piles frequently causes hard driving problems. A revised driving sequence often will alleviate this problem. This can often be a trial and error process. Driving from one side of the footing in a uniform heading helps. Driving from the center in a uniform outward pattern also can be helpful.

There are many factors which could contribute to hard driving and there are many solutions.

Because of the many variables involved, each hard driving problem must be evaluated on its own merit. There is no substitute for engineering judgement in this area. It should also be remembered that these are not infrequent problems and there is a broad base of experience to draw from within the Office of Structure Construction.

Occasionally, pile penetration to the specified tip elevation may not always be accomplished, despite the Contractor's best efforts. When this situation occurs, the Engineer may consider accepting piles that are not driven to specified tip. This solution, while it may solve the construction problem, may present administrative problems that will require resolution. Situations have been experienced where the foundation design was changed, during construction, from a driven pile foundation to another type of footing. Prior to making a decision to accept piles that are not driven to specified tip, or initiating a change in footing design, discuss the problem in detail with the Bridge Construction Engineer and, depending on the results of the discussion, with the Engineering Geologist and the Project Designer.

Soft Piles and Retap

In this situation, the pile has been driven to the specified tip elevation but the specified bearing value, as determined by the ENR formula, has not been obtained. The Standard Specifications require the Contractor to satisfy both requirements.

Following are some ground conditions that may produce soft driving:

CONDITION	DESCRIPTION
1	Loose submerged fine uniform sand. Driving temporarily produces a quick condition. Retap will probably not indicate capacity.
2	Cohesive soil. Driving temporarily breaks down the soil structure, causing it to lose a part of it's compressive strength and shear value. Retap should indicate increased capacity.
3	Saturated coarse grained pervious material. May display high driving resistance, but on retap will lose capacity as compared to the initial driving. This could be due to changes in pore water pressure within the soil mass.

The *Standard Specifications* provide that the "*s*" value (inches/blow averaged over the last few blows) in the ENR formula can be measured when the pile is retapped after a set period.

As in the case of attempting to define the term "refusal", there are as many interpretations of acceptable retap criteria as there are interpreters. Interpretations vary from no pile movement with maximum hammer energy to once or twice the required blow count in one foot of retap to the minimum blow count in 1 to 3 inches of retap.

When acceptable retap criteria is defined within the context of the Special Provisions, it will be apparent that the last of the above interpretations (minimum blow count measured over the initial several inches of retap) complies with the intent of the specifications. This statement is based on the specification requirement that application of the ENR formula is the basis of acceptance and, in this formula, pile penetration is measured over the last few blows. This is not to suggest that all pile inspection be directed toward measuring pile penetration this way. In fact most engineers prefer to use the more conservative approach and determine the penetration by counting the number of blows per foot or half foot.

The point of the above is to emphasize the purpose of the retap, which is to measure the ground "take-up" that has taken place over a given period. Hence, the effort needed to get the pile moving is of prime importance and should be the prime consideration when determining acceptability of the piles. Most engineers will argue that once the "take-up" resistance is overcome (the pile "breaks loose"), the pile will display characteristics identical to those when it was driven initially.

The *Standard Specifications* do not specify elapsed time before attempting a retap. Hence, trial and error methods have to be employed. On contracts where soft driving in clay materials is anticipated, specific retap guidelines are frequently given in the Special Provisions. The period is usually set at a minimum of 12 hours unless bearing is obtained sooner. In addition, only a fixed percentage of the piles are retapped (10% or a minimum of

2 per footing). However, when retap requirements are not listed in the Special Provisions, it is up to the Engineer to determine what criteria will be used to determine pile acceptability. At times piles will not attain minimum bearing at specified tip, even if retapped. In these cases the Contractor is obligated to furnish longer piles to accomplish the work. While this situation rarely happens with precast concrete piles, prudent contractors will drive "test" piles at various locations on the job to confirm lengths prior to ordering piles. This should be suggested to the Contractor before work starts. In the case of steel "H" piles, this situation happens frequently. If overdriving is excessive, lugs or "stoppers" can be welded on the pile to mitigate the problem. If lugs are not required by the contract, they can be added by change order. Bridge Construction Memo 130-5.0 covers this problem in detail.

Alignment of Piles

Watch the alignment of each pile. This is extremely important if swinging leads are used. Immediate correction should be made if the pile begins to move out of plumb. Driving may have to be stopped and the pile may have to be pulled and redriven.

The *Standard Specifications* state that piles materially out of line will be rejected. This brings up the question as to what is "materially out of line". Some contracts have a specific tolerance in the Special Provisions as to alignment and/or plumbness of the piles. This is usually due to special considerations in the design of the structure. Each situation should be analyzed separately and "engineering judgment" used in making final determination as to the acceptability of any misaligned piles.

Overdriving

Occasionally the Contractor will want to overdrive prefabricated piles to avoid cutting piles to grade. This can be allowed in some circumstances. However, no payment is allowed for the additional length driven below the specified tip elevation. This subject is covered by Bridge Construction Memo 130-6.0.

Safety

The potential for an accident around pile driving is probably greater than for any other construction operation. The pile rig with a set of heavy leads and hammer is unwieldy enough; add a long pile and a high potential for danger exists. Add a hammer in operation with its moving parts, perhaps a steam or high pressure line, and the need for awareness is obvious.

Following are some of the items that individuals inspecting piles should be aware of, especially new personnel:

ITEM NO.	DESCRIPTION
1	Stand away from the pile when it is being picked and placed in the leads. Sometimes the pile when dragged will move in a direction not anticipated.
2	Stand as far away from the operation as practical to do the work.
3	Keep clear of any steam or air lines.
4	Watch the swing of the rig so as not to be hit by the counterweight.
5	Wear safety glasses. There is a high incident of flying debris during the driving operation (dirt from piles, concrete from piles and steel chips).
6	Keep an eye on the operation in progress. Look out for falling tools and materials from the pile butts. Watch the rig in case the leads start to fall or the rig starts to tip.
7	Hearing protection is required due to high noise levels.
8	Have a planned route for rapid escape. If required to move quickly there will not be time to look around first.
9	Wear old clothes. Park your car and stand upwind when possible. Diesel oil does not wash out of clothes!
10	Look where you are walking. The protective covers may be off the predrilled holes.
11	Welding must not be viewed with the naked eye. Shield eyes when in the vicinity of a welding operation and wear appropriate shaded eye protection when inspecting this work.